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STUDY OF INDUSTRIAL USES OF ENERGY
RELATIVE TO ENVIRONMENTAL EFFECTS

INSTITUTE OF GAS TECHNOLOGY

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

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The energy utilization patterns and air pollutant emissions of the 10 largest energy-consuming industries in the U.S. are presented in this report. Each industry is described in terms of basic energy-consuming processes, and the amount and types of energy consumed and the air pollutant emissions for each process (especially those related to combustion) are presented. The energy utilization efficiency of each process is discussed with a view toward increasing efficiency either by improvement of the existing process or by replacement with a new process. In addition, the effects of such changes on the air pollutant emissions are determined.

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I. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The objectives of this study were 1) to identify where and how energy is being used by industry, 2) to determine the relationship between energy use and its impact on the environment, and 3) to determine how new technology or changes in existing technology will affect energy utilization and air pollutant emissions by industry on a nationwide basis.

The 12 industries examined in this study account for more than 60% of the primary energy consumed by industry in the U.S., or about 20% of the total energy consumption of all energy-consuming sectors. This study has determined the energy consumption of each industry on an overall basis and on a process-by-process basis, indicating those processes in which the energy utilization efficiency can be increased either by replacement with an alternative process or by improvement of the existing process. For example, the use of oxygen in a fuel-fired reverberatory melter reduces total fuel consumption, even when the energy consumed in making the oxygen is considered.

In addition to energy utilization, air pollutant emissions were considered on a process-by-process basis. Actual emission rates as well as methods of reducing emissions are presented for those types of emissions and processes for which information is available. Where applicable, these emissions are related to the types of fuel consumed by each process, and the effects of changes in process technology on these emissions are considered.

By using the data collected during this study, the energy consumption and air pollutant emissions of each industry are projected to 1985. In general, these projections are based on historical trends and projections published by each industry and, as such, may be subject to much debate. The projections have been made only to 1985 because the uncertainty increases as the time covered increases. The uncertainty is much less for a period between now and 1985; industry is essentially locked into its current pattern of energy consumption, in large part, because of the long time lags in implementing new processes on a large enough scale to affect the total industrial-energy-consumption pattern. In addition, much of the research and development in industry has been aimed at objectives other than energy conservation, resulting in the availability of only a very

limited number of new energy-conservative technologies. Even conservation techniques that are more easily implemented, such as proper maintenance and operating practices, can require years before any significant decrease in energy consumption is observed. However, after 1985, the options for altering industrial energy consumption patterns increase considerably, and the future pattern of industrial energy consumption depends upon whether or not industry exercises these options.

The results of this study are valuable because they represent a reasonably compact compilation of data on current industrial process energy utilization and air pollutant emissions that can readily be used as a starting point for determining the future impact of new processes, energy conservation techniques, and air pollution control methods. The study also presents a large amount of information on new processes that could affect energy utilization and air pollutant emissions in the future if they are implemented. Because this study was based solely on published information, the acceptability of new processes to industry could not be determined. Consequently, the projections that consider the effects of new processes on energy utilization and the environment are only illustrative.

In 1972, the latest year for which information is readily available, industry in the U.S. consumed slightly more than 20.6 quadrillion Btu of energy, approximately 28.5% of the total national energy consumption. Table 1 summarizes the energy consumed in the U.S. by major sector. The industries investigated in this program consume approximately 12.7 quadrillion (10^{15}) Btu/yr, which is about 61.5% of the total energy consumed by all industry. The energy consumption of these industries in 1985, as determined by information collected during this program, is projected to be approximately 17.2 quadrillion Btu/yr, an increase of about 35.6%. This agrees closely with the 35% increase in energy consumption forecast by the Department of the Interior for the entire industrial sector for 1985. Table 2 summarizes the 1972 energy consumption of the industries examined during this program and contains projections to 1985. For the purpose of comparison, energy consumption data for the entire industrial sector also are presented. The projections of energy consumption in this table do not reflect changes due either to energy conservation programs or to replacement of current processes by new processes.

Table 1. ANNUAL CONSUMPTION OF ENERGY IN THE U.S. IN 1972*

	Natural			Other	Total (Gross)	Purchased	
	Coal	Gas (Dry)	Petroleum			Electricity	Total
				10 ¹² Btu			
Household and Commercial	395	7,642	6,735	0	14,772	3,482	18,254
Industrial	4,377	10,591	5,606	36	20,610	2,488	23,098
Transportation	4	790	17,318	18	18,130	18	18,148
Electricity Generation	7,827	4,102	3,141	3,513	18,583	--	18,583
Miscellaneous	0	0	165	0	165	0	165
Total	12,603	23,125	32,965	3,567	72,260	5,988	78,248

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* Source: Division of Fossil Fuels, Bureau of Mines, U.S. Department of the Interior, press release of March 1973.

Table 2. ENERGY CONSUMPTION BY INDUSTRY
FOR 1972 WITH PROJECTIONS FOR 1985

<u>Industry</u>	<u>Total Annual Energy Consumption</u>	
	<u>1972</u>	<u>1985</u>
	<u>—10¹² Btu—</u>	
Iron and Steel	3,040	4,100
Glass	250	450
Primary Nonferrous		
Copper	71.4	130
Lead	13.3	16.5
Zinc	38	51
Aluminum	352	1,100
Industrial Chemicals	3,764	4,900
Petroleum Refining	2,861	3,700
Plastics Materials and Synthetics*	134	700
Structural Clay	175	205
Paper and Paperboard	1,307	1,700
Hydraulic Cement	<u>581</u>	<u>700</u>
Total	12,685	17,209
Total Industrial Sector	20,731	28,170

* Excluding feedstocks.

In addition to energy utilization, this study also considered the effects of new processes and energy conservation methods on air pollutant emissions. As in the case of energy utilization, this study presents a base case of emissions by process. Unfortunately, the amount of available published data is very limited, and there are many gaps in this information, particularly for oxides of nitrogen (NO_x) and carbon monoxide. Furthermore, when the potential effects of a new process on energy utilization can be determined by calculation, the effects of a new process on air pollutant emissions generally cannot be determined because emission rates cannot be determined except under actual operating conditions. There are some exceptions, such as new hydrometallurgical processes from which the air pollutant emissions are extremely small because these are basically wet chemical processes. Table 3 summarizes the total annual air pollutant emissions from all sources in 1968, the latest year

Table 3. ESTIMATED NATIONWIDE AIR POLLUTANT EMISSIONS IN 1970

Source	Carbon Monoxide	Particulates	10 ⁶ tons/yr		
			SO _x [*]	Hydrocarbons	NO _x [†]
Transportation	111.0	0.8	1.0	19.5	11.7
Fuel Combustion in Stationary Sources	0.8	6.7	26.4	0.6	10.0
Industrial Processes	11.4	13.3	6.4	5.5	0.2
Solid Waste Disposal	7.2	1.4	0.1	2.0	0.4
Miscellaneous	18.3	4.0	0.2	7.3	0.5
Total	149.0	26.2	34.1	34.9	22.8

* SO_x expressed as SO₂.

† NO_x expressed as NO₂.

for which this specific information is available. Industrial air pollutant emissions cannot be determined from information collected on each industry because not enough information on actual operating conditions, such as the number of plants using a specific type of pollution control device, is available.

The data collected during this program suggest that the implementation of control devices will have the greatest impact on air pollutant emissions from industrial processes. Implementation of new processes is not likely to have a reducing effect on the emissions. On the other hand, if a new process aggravates the pollution problem by creating higher emissions, even if it reduces energy consumption, pollution control devices would have to be used. There is a tendency, however, to develop new processes in which air pollutant emissions, although not reduced per se, are more readily controllable than those from an older process. Numerous examples of this trend exist in those industries in which sulfur emissions are a serious problem. The trend in these industries is to develop a new process that actually causes higher sulfur emissions than the old process, but because of the higher concentrations of sulfur, control in the form of sulfuric acid plants becomes feasible. In other industries, equipment is redesigned to allow for air pollutant emission controls that could not be used with the older equipment. In spite of these steps, reduction of air pollutant emissions from industrial processes is likely to be realized only over a long period. Note that the type of fuel consumed will affect process air pollutant emissions, but only if proper control methods are not implemented. Certainly the type of fuel consumed affects the method of control used, but the end result should not be affected by fuel type.

The utilization of energy by industry can be broken down into four basic categories: process heat, steam generation, electricity generation, and feedstock. Most of the electricity used by industry is purchased. Table 4 summarizes the energy consumption by each of the industries investigated during this program according to the category in which the energy was consumed. The amount of energy consumed by an industry in each of these categories varies from as little as 5% to as much as 95%. Thus, the energy utilization pattern of industry is diverse, and few solutions can be common to all industries.

Table 4. ENERGY UTILIZATION BY SPECIFIC INDUSTRIES

Industry	Annual Energy Consumption, 1972 10 ¹² Btu	%		
		Percentage Consumed for Process Heat	Percentage Consumed for Steam Generation	Percentage Consumed as Feedstock
Industrial Chemicals	3764	55	16	29
Iron and Steel	3040	80	20	0
Petroleum Refining	2861	60	20	20
Paper and Paperboard	1307	5	95	0
Hydraulic Cement	581	90	10	0
Primary Nonferrous Glass	497	80	20	0
Structural Clay Products	250	90	10	0
Plastics and Synthetics	175	90	10	0
	755	10	45	45

Examination of these data indicates that some industries, because of their particular energy utilization pattern, are more likely to experience reductions in energy consumption in the future than other industries. For example, the paper and paperboard industries consume about 95% of their total energy in the generation of steam. Because the fuel efficiency of steam generation is high (generally in excess of 80%), significant improvements are not likely in this area. Yet the energy consumption per unit of product probably can be reduced by improving upon the efficiency of steam utilization. The means for reducing steam utilization range from insulation of steam lines to substitution of direct-fired for indirect-heated processes. In those industries that generate large quantities of steam, therefore, reductions in energy consumption can be achieved by only a limited number of relatively simple means. However, data on the current operating conditions within each industry are not available; consequently, estimates of the potential reductions that can be achieved would be pure speculation.

Unlike steam generation production, energy consumed for process heat is very sensitive to reduction. In the past, American business economics dictated that productivity was of prime importance in equipment design and that efficient utilization of cheap energy was second, but the cost of energy is increasing. Consequently, the potential for new processes that will reduce energy consumption is great for many industries. In addition, the potential for improved fuel efficiency merely by improving operating practices is great. In many cases, only minor alterations are necessary.

Another way in which fuel efficiency can be improved is by proper maintenance of existing equipment and replacement of obsolete, inefficient equipment by modern, more efficient units. In many cases, the maintenance requirements for achieving significant improvements in fuel efficiency are relatively simple, such as the sealing of air leaks on a furnace. With only minor modifications to current operations and with improved maintenance schedules, an estimated 10% or greater reduction in energy consumption can be achieved by industry. The effect of replacing obsolete, inefficient equipment cannot readily be determined without an accurate inventory of existing equipment, but such replacements are likely to result in substantial reductions in energy consumption.

During this program, several new processes that were found to exist would, if implemented, result in substantial reductions in energy consumption without detrimental effects on the environment. Yet many of these processes are being ignored by the respective industries for reasons that cannot readily be determined without the input of industrial representatives. A case in point is the use of oxygen enrichment to reduce fuel consumption in the glass industry. Although the effectiveness of this technique has been demonstrated on a full-size production facility, it has not gained widespread acceptance by the industry. As a result, only the company that successfully tested this fuel reduction method is actually using it. Because of this type of situation, it would be improper to advocate a changeover to this process or other new processes by U.S. manufacturers without first determining and evaluating the reasons for their reluctance.

The information presented in this report can and should be used to establish the basis for energy conservation programs within industry. Although it is very difficult to evaluate these programs on a nationwide basis, the information is complete enough that planning can be effectively accomplished for individual industries. Given these considerations, we recommend that the following tasks be undertaken:

1. The information contained in this report should be distributed to industry representatives to obtain the feedback necessary for complete evaluation of new processes or methods for reducing energy consumption. We think that many of the new processes discussed within this report offer viable alternatives to current processes with their high energy consumption patterns and, as such, should be implemented. However, industry feedback is required to determine other factors, such as economics, not covered by this study.
2. In areas in which new technology has been developed and subsequently ignored, programs should be implemented to demonstrate the effectiveness of the technology. This report presents information, when possible, that permits a decision to be made on which new process, if implemented, offers the greatest benefits. For processes for which specific information is lacking, programs should be implemented to obtain this information, such as economic factors and air pollutant emissions.
3. As indicated in this report, certain industries are more sensitive to efforts to reduce energy consumption than others. These industries, such as the primary metals, cement, and glass industries, are characterized as large consumers of energy in direct-fired heating processes and, consequently, are the industries upon which efforts should

be concentrated. Industries characterized as large consumers of such energy as boiler fuel should receive only secondary levels of effort because the potential for reducing their energy consumption is low.

4. Industries that consume large amounts of electricity or that propose to implement new processes that consume electricity in favor of older fuel-fired processes should be examined closely. In many cases, the amount of energy consumed at the industry level is significantly lower with an electric process than with a fuel-fired process, but primary fuel consumption — due to the relatively low efficiency of electricity generation and transmission — is actually higher.* However, in a number of cases, such as induction heating and resistance heating, energy consumption including fuel consumed for electricity generation is lower than that for the corresponding fuel-fired furnace. Air pollutant emissions also will be affected by changes from fuel-fired processes to electric processes, although the extent of the effect will vary according to the source of electricity. In those cases in which the fuel used in the industrial process is cleaner than the utility fuel, the potential for increased emissions by conversion to an electric process is high. In those cases in which the industrial process and the utility boiler are oil- or coal-fired, the effect of such a conversion depends to a large extent on the controls imposed on a power-generating plant. In general, the data suggest that each process for which conversion to electricity is being considered be carefully evaluated — on the individual merits of that process — for its impact on national energy consumption and air pollutant emissions.

Note that this study did not attempt to deal with the rapidly changing fuel availability situation. We only indicated what processes could switch fuels and what fuel is currently favored.

* Fuel values used throughout this report are the same as those used in the 1972 Census of Manufactures Special Report, "Fuels and Electric Energy Consumed." Unless otherwise stated, the energy consumed for electricity generation was not included in the figures for industrial electricity consumption.

II. SIC CODES 262 AND 263 - PAPER MILLS AND PAPERBOARD MILLS

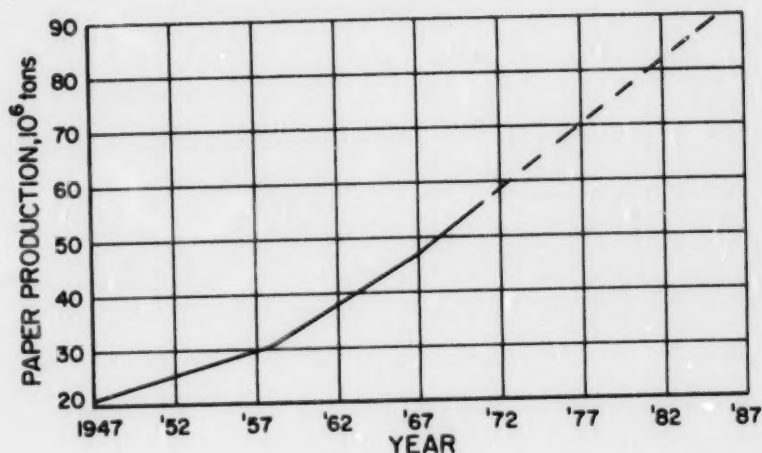
Summary

SIC Code 262 pertains to establishments primarily engaged in manufacturing paper (except building paper) from wood pulp and other fibers and also in manufacturing converted paper products. Pulp mills combined with paper mills, and not separately reported, are included in this industry. Establishments engaged in the manufacturing of converted paper products from purchased paper stock are classified elsewhere.

Similarly, SIC Code 263 pertains to establishments primarily engaged in manufacturing paperboard, including paperboard coated on the paperboard machine, from wood pulp and other fibers and also in manufacturing converted paperboard products. Pulp mills combined with paperboard mills, and not separately reported, are included in this industry. Establishments primarily engaged in manufacturing converted paperboard products from purchased paperboard are classified elsewhere.

Paper and paperboard mills consume nearly 10% of the total primary energy consumed by industry in the United States.⁵ In 1971, approximately 56 million tons of paper and paperboard was produced, requiring an estimated 1310 trillion Btu of energy. Major energy sources are natural gas (29.3%), electricity (6.1%), coal (17.6%), oil (25.0%), and by-product fuels (22%), such as bark and black liquor. Approximately 93% of the energy is used in boilers for steam production, and the remaining 7% is used for mechanical drives.

The growth rate of the paper and paperboard industry (Figure 1) has been greater, on the average, than that of the rest of industry; consequently, its relative energy consumption also has increased. In 1947, its share of the total primary energy consumed by industry was about 4.1%, compared with its current level of almost 10%.⁴ Because the fuel utilization efficiencies of boilers are very high, usually 80% or better, fuel consumption per ton of paper or paperboard produced is not likely to decrease in the future as a result of improvements in boiler efficiencies. However, certain heat requirements, in a given process for a given type of paper, can be reduced if the plants using the process become more efficient in their production.



A-44-698

Figure 1. ANNUAL PAPER AND PAPERBOARD PRODUCTION WITH PROJECTION TO 1985

These increases in efficiency usually are the result of improved methods of heat recovery and heat reuse and conversion to direct-fired processes when possible. These improvements reduce the amount of direct heat lost or wasted. Following this analysis one step further indicates that the new plants are the most efficient plants and that older plants that have undergone revisions in equipment and processing are less efficient but still significantly more efficient than older plants that have undergone no improvements. In general, the paper and paperboard industry tends to keep abreast of new developments, maintaining a very high degree of efficiency. In addition, competition is very strong so that inefficiently operated plants do not last long unless they produce highly specialized products. Thus, the efficiency of energy utilization probably will improve in the future.

Paper- and Paperboard-Manufacturing Processes^{1,4,7}

The manufacture of paper is divided into two basic operations: manufacture of pulp from the raw material and transformation of pulp into the finished product.

Pulping

The pulping process is most often a chemical process, although nearly 12% of total pulp production is by mechanical or semichemical processes. The chemical pulping processes are classified by the type

of liquor used to digest the wood chips. Of the available processes, the sulfate process (also known as the kraft process) and the sulfite process are the most widely used. These two processes account for nearly 88% of the pulp produced.³ The kraft process is by far the most popular. Figure 2 is a flow sheet of a kraft process for pulping and papermaking.

The mechanical processes are groundwood, in which wood blocks are held against a grindstone; steamed groundwood, which is similar to the groundwood process except that the wood is steamed for 6-12 hours prior to grinding; disk refining, in which the wood is cut into chips and ground between two disks rotating in opposite directions; and defibrator, which is similar to disk refining except that the chips are presoftened by steaming, soaking, or a mild chemical cook. This report deals only with the chemical processes because they consume the largest percentage of energy in the paper and paperboard industry.

The first stage in preparing logs for pulping is removing the bark. The discarded bark, which is saturated with water, is dried to a 50% moisture content and used as fuel for steam-raising in bark boilers. The calorific value of the bark depends upon the type of bark and the time of year when it was harvested, but a typical calorific value is 3500 Btu/lb of dry bark.⁷

The wood chips produced in a machine that cuts the debarked logs are cooked at high temperature and pressure in a liquor. In the sulfate process, this liquor is made up of sodium sulfate and sulfide. In the sulfite process, this liquor is bisulfite of lime. This process dissolves the lignin in the wood, leaving the fibers free. The spent liquor plus lignin (or concentrated black liquor), which is obtained from reduction of the water content to about 50% by flash evaporation, is fired in special boilers to raise steam. This black liquor is by far the most important by-product fuel in the paper industry; it has a calorific value of about 8000 Btu/lb.⁷ The black liquor, at about 190°F, is sprayed onto the flat sidewalls of the boiler, where further water removal and finally combustion take place. In the kraft process, the smelt is tapped from the furnace, quenched, and ground to recover chemicals, which after further preparation can be recycled into the cooking process.

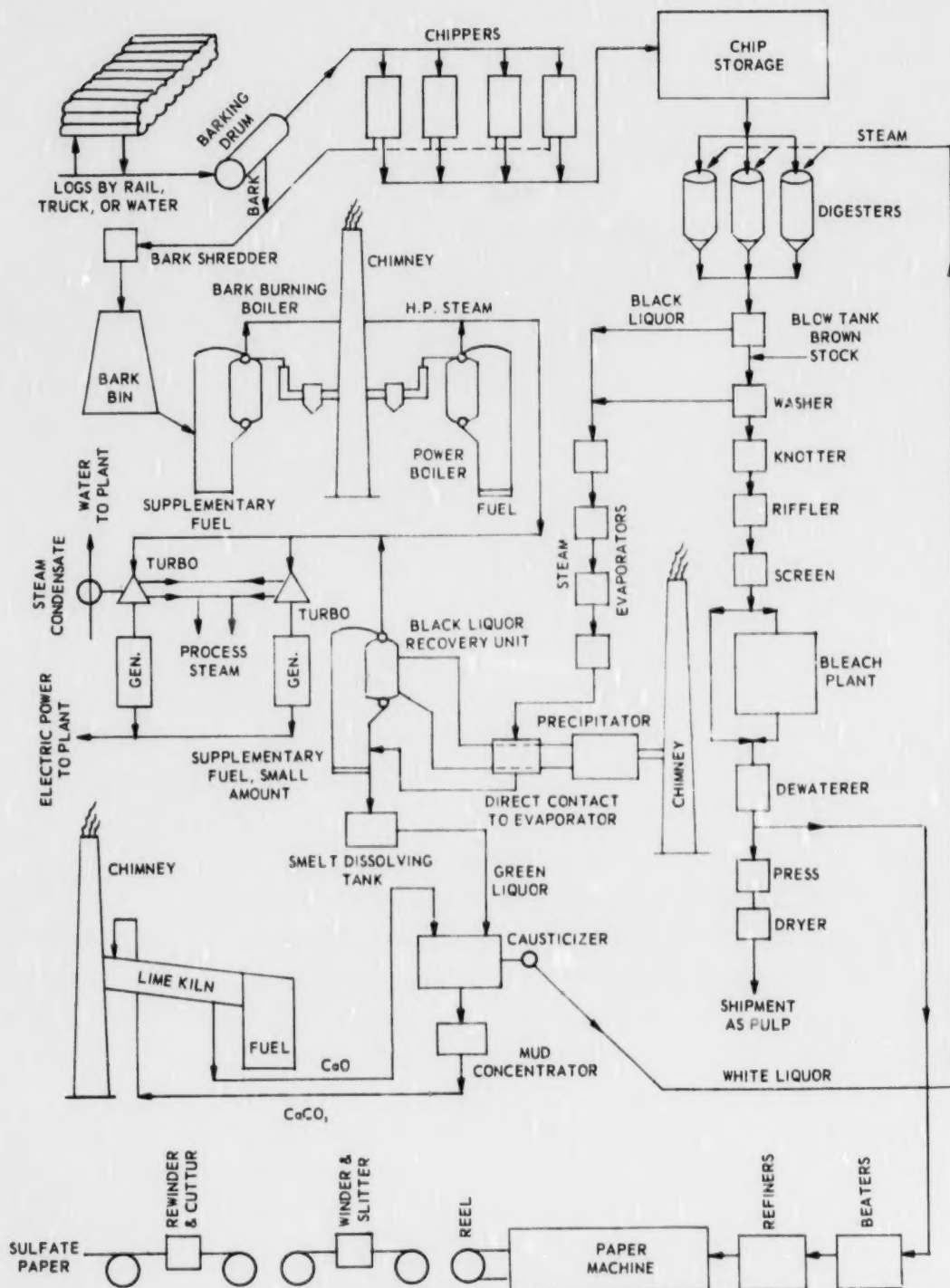


Figure 2. FLOW SHEET FOR SULFATE PULP AND PAPER¹

The pulp then is treated in a variety of processes, depending upon the end use of the product. In some cases, the water must be removed, although in an integrated mill, where pulping and papermaking are accomplished on the same site, very little water is removed. In general, the pulp is screened, separating coarse fibers from fine fibers and removing dirt and foreign objects. Depending upon the final product, the pulp may also be bleached.

Papermaking

Papermaking consists of four major mechanical steps: preparing the stock, forming the sheet, removing the water, and finishing the sheet. (The same is true in the manufacture of paperboard.)

Preparing the Stock

The fibers produced in the pulping process are mixed with water to form a very thin mixture containing 1 part fiber to 200 parts water. This paper stock is further refined in a process known as beating. The pulp is passed between two sets of bars, forming two rubbing surfaces. In this process, the fibers are shortened, the ends shredded, and the outer walls ruptured.

In many instances, again depending on the end product, mineral fillers are added to the stock; these fillers increase the paper opacity, improve printing quality, and increase brightness. The more important fillers are clay, calcium carbonate, and titanium dioxide. Finally, to retard the flow of ink in the paper, a "sizing" material is added to the stock.

Forming the Sheet

Upon completion of the stock preparation step, the stock is fed into a papermaking machine for forming the sheet. Figure 3 is a cross section of a typical paper machine. The prepared stock is stored in the headbox at a constant head and issued from the bottom of the headbox through a fine horizontal opening across the entire width of the machine onto a moving wire mesh. The wire mesh runs over rollers that remove the water from the sheet by gravity and capillary action. Thus, a vacuum is applied to the sheet for additional water removal. The water content of the sheet at this point is about 80% by weight.

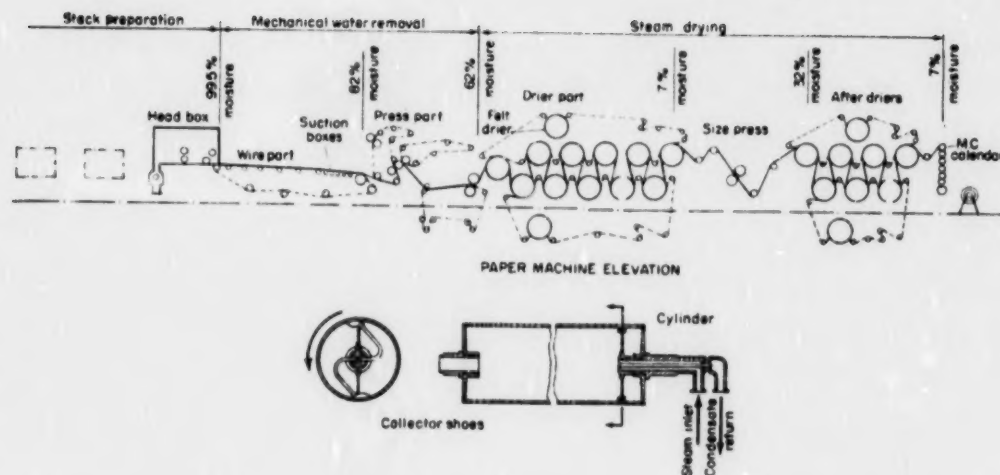


Figure 3. PAPER MACHINE ELEVATION WITH DETAIL OF TYPICAL STEAM SUPPLY AND CONDENSATE REMOVAL NOZZLE⁷

Removing the Water

The newly formed sheet is picked off the wire screen and supported on a continuous band of felt; it is passed through a series of mechanical presses that squeeze the water from the sheet. Usually two or three presses in series remove as much water from the web of paper as possible; yet at the end of the press cycle, the paper is still 62% water by weight. Upon leaving the press section, the paper enters the drying section, which is made up of a series of large-diameter, hollow rolls, which are heated with steam. The paper is passed over these rotating drums, supported on a system of felts that are designed to ensure continuous contact between the sheet and cylinder surface and to carry away from the sheet a part of the moisture evaporated. After leaving the dryer section, the sheet is only 6-7% water by weight and is capable of supporting itself.

Finishing the Sheet

The dried sheet enters the finishing section, where it is passed through the calendar section. Here, it is compressed to give it a smooth finish. In some cases, coloring may be added by the calendar rolls or a latex or a starch surface coating may be applied as a filler and glazing agent to enhance the printing quality. The coating usually is applied as an aqueous suspension; consequently, the sheet may be wetted up to 35%. Therefore, the sheet must be redried in a section that is identical to the main drying section, but is referred to as the after-dryer. After the finishing operation is completed, the paper is wound onto a reel, where it can be trimmed to the desired width.

Papermaking is a continuous process from the introduction of the stock into the paper machine through the finishing rolls. Although there are several variations and combinations of paper machines, there are two general types: the "Fourdrinier" and the "cylinder."

The Fourdrinier machine allows the pulp to flow onto a horizontal wire screen made in the form of an endless belt. The water in the pulp drains through the wire, assisted by suction boxes at certain points. The matted sheet of fibers is transferred to a wool felt belt, which carries it to the press section.

The cylinder machine consists of a cylinder covered with a wire screen revolving in a vat. The fibers are deposited on the screen as the water passes through the screen. The fibers are picked up on a felt belt and carried to the presses. Usually several cylinders are served by one "pickup felt" so that the sheet formed consists of several plies.

Energy Requirements for the Manufacture of Paper and Paperboard

Energy in paper and paperboard mills typically is consumed in two forms: steam and electricity. Process steam, which is required primarily for drying the paper, consists mainly of steam supplied to the drying cylinders, heat for air being supplied to the machine, heat for conditioning the air in the machine house to maintain satisfactory ambient air conditions, and direct steam heating for stock preparation as necessary. In the pulping process, steam is used by the digesters, the

washers, and the evaporators. Electricity is used primarily for mechanical drives - in barking and chipping processes, in chemical pulping, as well as in mechanical pulping processes. Electricity also is used to drive the paper machines.

Table 1 is an estimated breakdown of the energy consumed by fuel type and end use in 1971.

Table 1. ESTIMATED FUEL CONSUMPTION BY
PAPER AND PAPERBOARD MILLS IN 1971

<u>Fuel Type</u>	<u>Consumption, 10¹² Btu</u>	<u>Usage</u>
Coal	230	Steam generation [†]
Fuel Oil	327	Steam generation
Natural Gas	383	Steam generation, heat
Other Fuels (Bark and Black Liquor)	288	Steam generation
Purchased Electricity*	80	Mechanical drives

* 110 trillion Btu was consumed as steam for electricity generation.

† 901 trillion Btu was recovered and reused for steam generation.

The table shows that all forms of energy are used by the industry, mainly for steam generation. However, because steam must be generated in any case, a mill typically generates much of its own electricity. In 1971, an estimated 53% of the electricity consumed by paper and paperboard mills was self-generated.

Although information quantitatively relating energy type to steam generation is available, accurate figures on steam consumption by process are not readily obtainable because the same fuel is used several times. For example, if a plant requires quantities of electricity, steam, direct firing, etc., the statistics on paper production in the plant may reflect uses of electricity, steam, and gas that all originate from the same source. As previously stated, much of the energy consumed in a specific process is energy that has been recovered from other processes in the plant, which in turn can be traced to a specific fuel. If energy consumptions

by process are simply added together to determine the total energy consumed for the production of a unit weight of paper, the resulting figures on the actual amount of energy consumed — the energy input — would be inflated. Furthermore, papermaking processes vary from plant to plant, depending upon the age of the plant and the specific processes being used. And finally, statistics on the processes used in a plant are well guarded because the industry is very competitive.

Pulping

Although specific energy consumption figures are not available for each step in the pulping and papermaking processes, generalizations can be made. In the kraft pulping process, energy is consumed 1) for bark-ing, 2) for chipping, 3) for digesting, 4) for washing, 5) in the evaporators, 6) in the recovery plant, and 7) in the recausticizing operation. Steps 1 through 4 deal with the actual pulping process, and steps 5 through 7 deal with the recovery of the chemicals used in the pulping process. In other pulping processes, the chemical operations are different or, in the case of mechanical processes, are eliminated altogether, in which case the energy requirements change. Of all the pulping processes used, the kraft process not only is the most widely used but also consumes, in general, less energy than the other pulping processes. Based on an energy input to a pulp and paper mill of about 23 million Btu/ton of paper produced, the pulping process consumes about 15 million Btu/ton of paper produced. However, approximately 25% of paper production is accounted for by recycled paper, which requires only 25% of the steam and 10% of the electricity required for wood pulping processes. A more realistic energy consumption for pulp manufacturing is about 18 million Btu/ton of pulp produced. On this basis, approximately 766 trillion Btu of energy was consumed for pulping processes in 1971.

Paper and Paperboard Machines

The typical paper machine uses energy, primarily as steam, for drying the paper as it is fed through the machine. Electricity is used for driving the machines. Although the energy consumed by the paper machine depends upon several factors, an average value* is about 8.0

* Purchased electricity included.

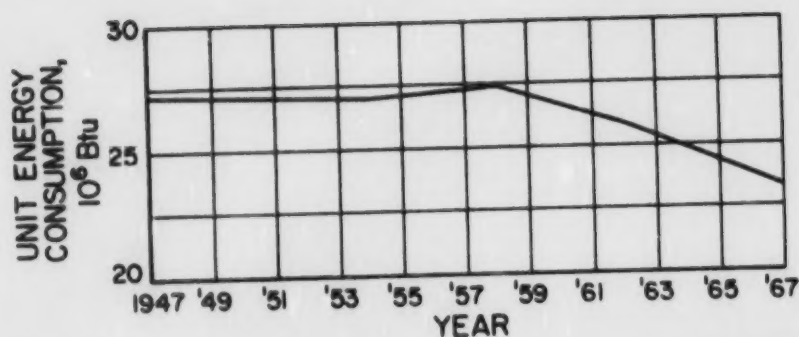
million Btu/ton of paper.⁷ On this basis, approximately 450 trillion Btu of energy was consumed by paper and paperboard machines in 1971.

In a paper machine, the efficiency of energy utilization depends upon the ability to dry the paper as fast as possible, yet maintain the quality of the paper. This, in turn, also depends upon the effective transfer of heat from the steam in the cylinders to the paper web. The factors that affect the heat-transfer rate are the condensing temperature of the steam and the condition of the internal cylinder wall. The main requirement in a paper machine is that the temperature be evenly distributed across the width of the cylinder presented to the paper. How this is done often dictates the efficiency of heat transfer. For example, early machines utilized a steam system in which the steam entered a cylinder, was condensed, and was discharged through steam traps on each cylinder. On many installations, a common steam header supplied steam to all cylinders and a common condensate header discharged into a flash tank. More recently, it has been found that, by allowing up to 30% of the steam to blow through the cylinders, heat transfer and uniformity can be improved. Another factor that affects the energy utilization of a paper machine is the use of after-dryers. After-dryers can increase the steam conservation of a machine by as much as 30%.

Energy Utilization Pattern

As previously stated, the energy consumption pattern of the paper industry by process cannot be determined from a fuel input basis because of the large amount of waste heat that typically is recovered and reused in a paper mill. Still, generalizations about energy usage can be made.

Since 1958, the unit consumption of energy in the paper industry has been decreasing. (See Figure 4.) Several trends and developments are responsible for this decrease: 1) the increase in kraft paper production, a process that generally uses less energy than the other pulping processes, and 2) the increase in the use of more efficient continuous digesters, rather than the batch types previously used. Other trends that have appeared tend to increase energy consumption.



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Figure 4. ENERGY CONSUMPTION PER TON OF PAPER PRODUCED FROM 1947 TO 1967

The use of waste or recycled paper in the production of paper and paperboard has been decreasing, resulting in an increase in the use of wood pulp. Because paper made from wood pulp requires roughly 4 times as much energy as that made from waste paper, energy consumption increases. Current indications are that this trend may be reversing itself for ecological reasons. Another trend has been established with the increased interest in air and water pollution control: the installation of electrostatic precipitators, wet scrubbers, and other control devices, which has resulted in an increase in energy consumption.

In spite of these trends, unit energy consumption has decreased and is likely to continue to decrease as more recycled waste paper is used and more efficient means for drying the paper web in the paper machine are developed.

New Technology and Its Effects on Energy Consumption

Because almost all the energy consumed by the paper industry is converted to steam and then used, the technology for energy utilization is quite restrictive. New technologies for improving energy utilization are limited primarily to the improvement of boiler efficiencies, which would directly influence energy consumption, or to the improvement of steam utilization, which would indirectly influence energy consumption. In this industry, most of the development work is being directed toward the improvement of steam utilization. Some work is being done to develop direct-fired processes; such processes also would result in energy savings.

The paper machine is continually undergoing changes to improve the rate of drying, which in turn reduces energy consumption. In recent years, two important developments have resulted in reductions in energy consumption per ton of paper produced. Simply by using modern materials and equipment, the rate of mechanical water removal from the sheet of paper in the vacuum and press sections of the machine was increased. As a result, less water must be evaporated from the sheet in the drying cylinder section. The effect on energy consumption is an increase in electric consumption because of the increased contact loading of the presses and increased vacuum at the section boxes. But this increase is more than offset by the reduction in steam consumption. A comparison of machinery performance before and after redesign is given in Table 2. These data indicate that a 10% reduction in energy consumption is possible.

Table 2. THE EFFECT OF IMPROVED MECHANICAL WATER REMOVAL ON MACHINERY PERFORMANCE⁷

	<u>Before Redesign</u>	<u>After Redesign</u>
Maximum Output, tons/hr	5.9	7.1
Electricity Used, kW/ton	357	462
Total Steam Used in Cylinders, lb/ton of paper produced	8180	6000
Total Steam Used, lb/lb of water removed	2.06	1.43
Increase in Energy Consumption Due to Increase in Electricity Used, Btu/ton		358,000
Decrease in Energy Consumption Due to Decrease in Steam Used, Btu/ton (at 1350 Btu/lb of steam)		2,943,000
Net Decrease in Energy Consumption Due to Redesign, Btu/ton		2,585,000

The second development of importance is the use of forced-convection heat transfer for drying paper in conjunction with the drying cylinders. In this type of system, heated air is blown through a pattern of nozzles onto the outside surface of the paper. This increases the evaporation rate of the water in the paper. The extent of the increase depends on the temperature of the air and its coefficient of heat transfer to the paper surface being dried. The use of such a system can double or even triple

the normal maximum evaporation rate of 3 lb of water per sq ft of heated cylinder surface per hour, which is obtained by using only steam-fed cylinders. However, because of the high air temperatures (400°F+), direct-fired heaters that burn light fuel oil or natural gas are used. There is no information on the extent to which these processes are used in the industry, nor is there any basis for determining the real effects of these developments on the industry.

In addition to the developments just discussed, much work is being done with the objective of improving product quality and, at the same time, reducing costs. The work is still only in the experimental stages; thus, no operational data are available for analysis. However, once applied, these developments probably will decrease unit energy consumption.

At present, a direct heating application is being tested in a plant. This application utilizes two gas-fired infrared burners, each about 1-5 million Btu/hr, which cover the width of the paper machine. They are installed between the mechanical press section and the first drying cylinder to provide sensible heat to the wet paper web. This allows the first drying cylinder to be used for direct evaporation of moisture, which in turn increases machine output.

Much work has been done to develop a technique for using fluidized beds for drying paper webs. Although the results have been promising, the consumption of mechanical energy seems to be excessive.

Finally, work is being done to develop heat recovery systems that can simply be attached to older machines. Such a system would no doubt have a favorable impact on unit energy consumption in the industry.

Air Pollutant Emissions From Paper and Paperboard Mills^{2,6}

The major emissions from a kraft pulp and paper mill are particulates and odor. Odor is by far the most serious problem. These odors, which are characteristic of all kraft mills, are caused by various sulfur compounds released from several sources. Table 3 summarizes the average emissions from a kraft pulp mill without controls. The emissions are presented as discharges from the major mill components per ton of pulp produced. Note that, according to these data, the paper machine is not a source of emissions. The following discussion addresses the emissions from each process and the possible systems that can be used to control them.

Table 3. AVERAGE KRAFT PULP MILL
POTENTIAL EMISSIONS WITHOUT CONTROL²

<u>Department</u>	<u>Particulates</u>	<u>Sulfur</u> [†]
	<u>lb/ton</u>	
Digester		
Batch	0	2.5
Continuous	0	1.5
Washers	0	0.5
Bleach Plant*	0	2.0 [‡]
Evaporators	0	3.5
Recovery Furnace	170	10.0
Dissolving Tank	5	0.15
Lime Kiln	45	1.0
Power Boiler (Hog Fuel)	35	0.01
Paper Machine	0	0

* Six-stage bleach plant - CEHDED.

† Does not include sulfur as SO₂.

‡ Chlorine as lb/ton.

Digesters

Digesters are a large source of odor in a pulp mill. The major malodorous compounds are methyl mercaptan, dimethyl sulfide, dimethyl disulfide, and traces of hydrogen sulfide.⁶ (These compounds are included as sulfur in Table 3.) These emissions are released during the cooking and discharging of the pulp to the blow tanks. A large quantity of steam is released during the blow of a batch digester, but normally it is condensed.

The control systems used on the digesters depend on whether the process is batch or continuous. Part of the problem with a batch digester is that the flow of gases to be treated is highly variable. Figure 5 is a diagram of a system used for controlling emissions from a batch digester. In this system, the relief gases are directed to a relief condenser, where the turpentine is condensed and stored for disposal by sale or burning. The noncondensable vapors are eventually piped

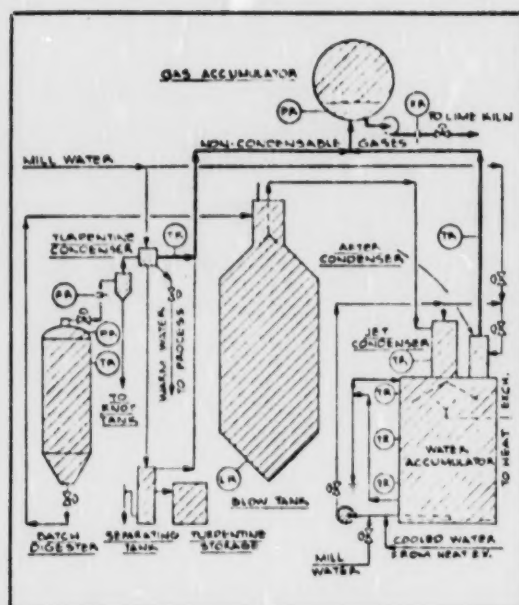


Figure 5. FLOW DIAGRAM OF AIR EMISSIONS FROM BATCH DIGESTER²

to the lime kiln, where they are completely burned. The other sources of odor in the digester area are the condensates from the turpentine recovery system and from the accumulator blow heat recovery system. The odorous gases that are dissolved in these liquids can be stripped with steam or air and then discharged with the stage seal tank overflow from the bleach plant.

In the case of a continuous digester, the control system is simplified, as shown in Figure 6. Here, the relief gases from the low-pressure steaming vessel go to a condenser, where turpentine is condensed. It is then stored for sale or burning at a later time. The noncondensables go directly to the lime kilns. The flash from the black-liquor flash tank goes to a condenser, and noncondensable gases containing sulfur compounds are likewise destroyed in the lime kiln.

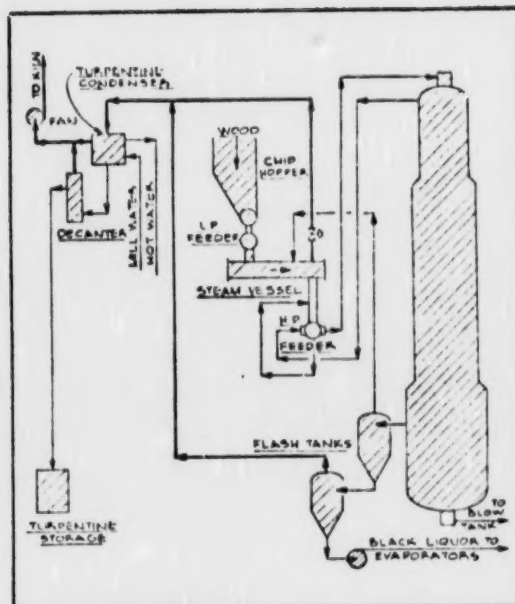


Figure 6. FLOW DIAGRAM OF AIR EMISSIONS FROM A CONTINUOUS DIGESTER²

Washers

The main emissions from the washers are the sulfur compounds mixed with vapors from the pulp-washing cycle. Conventional systems using vacuum filters expose the pulp and liquor to the air, releasing sulfur compounds, which are discharged to the atmosphere. If pressure-washing systems are used, emissions come only from liquor storage tanks. In this case, the volume is considerably less.

Emission controls for this process involve enclosure of the washers in vented hoods. The discharges then can be collected and directed toward a thermal oxidation unit, such as a recovery boiler, where the offensive vapors are destroyed. All black-liquor storage tanks also can be vented to a common duct, which then directs the discharge to a thermal oxidation unit.

Evaporators

The black liquor that is fed to the evaporators normally is oxidized to stabilize sulfur compounds, thus preventing their loss during subsequent evaporation and burning operations. The discharge from the oxidation system contains sulfur compounds.

The objectionable emissions from the evaporators also are sulfur compounds. These compounds are distilled off in the evaporation process in low volumes, but they contain high concentrations of hydrogen sulfide, mercaptans, dimethyl sulfide, and dimethyl disulfide.

The noncondensable gases evolved from the evaporators may be scrubbed with white liquor or piped to the lime kiln for incineration. If they are scrubbed, the hydrogen sulfide and mercaptans can be recovered and returned to the liquor system. The remaining sulfides then are destroyed by burning.

Recovery Boilers

Both particulates and sulfur compounds are emitted from the recovery boilers as a result of the combustion of the black liquor. Improper furnace operation can result in the emission of large quantities of sulfur compounds. In general, the emissions are controllable as before. Particulates are controlled by electrostatic precipitators or wet scrubbers or both. An efficiency of at least 99% can be achieved with electrostatic precipitators.

Odor control of effluents from the recovery boilers can be achieved in two ways. In one case, the black liquor is oxidized, thus fixing the sulfur compounds and causing them to remain in the chemical recovery system rather than to be discharged into the atmosphere. The alternative is to eliminate the direct-contact vaporizer at the recovery furnace. Normally the hot flue gases from the furnace release sulfur compounds from the black liquor in the direct-contact evaporator. By eliminating this system, the emissions also would be eliminated.

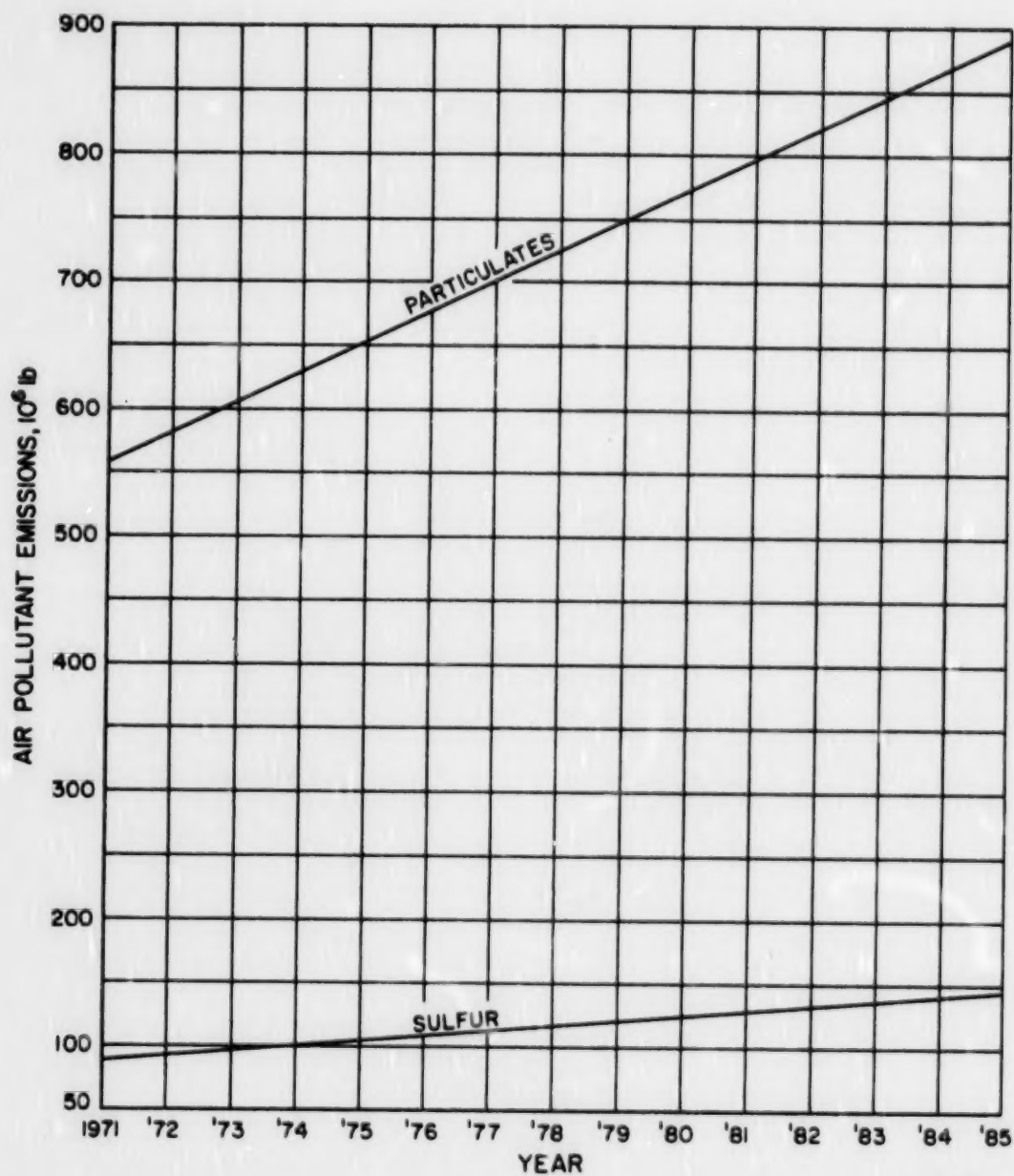
Lime Kiln, Dissolving Tank, and Power Boilers

The major emission from lime kilns, dissolving tanks, and power boilers, which burn hog fuel, is particulate matter. Particulates from lime kilns result from entrainment of the dust in the flue gases. In the dissolving tank, vapors are generated as the result of the reaction between the smelt from the recovery boilers and water in the tank. These vapors entrain chemicals as particulate matter and are vented from the tank. The preferred systems for controlling particulate emissions from both the lime kiln and the dissolving tanks are scrubbers. In the case of the power boilers, cyclone filters or cinder collectors can be used satisfactorily.

In general, air pollutant emissions from paper mills can be controlled. Table 4 summarizes the emissions from a typical plant after suitable control equipment has been installed.

Table 4. AVERAGE KRAFT PULP MILL
AIR EMISSIONS WITH CONTROL²

<u>Department</u>	<u>Particulates</u>	<u>Sulfur</u>
	<u>lb/ton</u>	
Digester		
Batch	--	--
Continuous	--	--
Washers	--	--
Bleach Plant	--	--
Black Liquor Oxidation	--	0.3
Evaporators	--	--
Recovery Furnace	3.5	1.0
Dissolving Tank	0.5	0.1
Lime Kiln	1	0.2
Power Boiler (Hog Fuel)	5	0.01
Paper Machine	--	--



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Figure 7. PROJECTED ANNUAL AIR POLLUTANT EMISSIONS FROM KRAFT PULP MILLS WITH CONTROLS

These data indicate that most of the emissions, particularly the most objectionable ones, are virtually eliminated by more or less conventional means. In spite of these controls, an estimated 560 million pounds of particulates and 90 million pounds of sulfur were emitted in 1971. These figures, as shown in Figure 7, are expected to climb to 890 million and 143 million pounds, respectively, by 1985.

Improved fuel utilization efficiency within this industry will occur primarily as the result of improved steam utilization. Consequently, the less fuel burned for steam generation, the less air pollutants will be emitted from the boilers as a result of this combustion. These emission factors cannot be quantified because they depend on the specifics of the fuel, such as ash and sulfur content of coal and sulfur content of oil. Other emissions are not expected to be affected by implementation of new technologies.

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III. SIC CODE 281 - INDUSTRIAL CHEMICALS

Summary

The industrial chemicals industry covers a very wide range of products; consequently, the survey of this industry can be approached in a multiplicity of ways. For this report, the major chemical groupings (i. e., alkalies and chlorine, gases, inorganic chemicals) are discussed, with emphasis on the most important chemicals from the point of view of production and energy consumption. Although SIC Code 281 applies to industrial inorganic chemicals only, this section also covers certain organic chemicals (SIC Code 286) such as benzene and toluene. Finally, this section covers certain miscellaneous chemicals (SIC Code 289) such as carbon black.

The industrial chemicals industry is the largest energy-consuming sector of industry. In 1971, the industries classified under SIC Code 28 (chemicals and allied products) consumed an estimated 5107 trillion Btu of energy for process heat, mechanical drives, and feedstock. Of this total, 3764 trillion Btu of energy, about 74% of the total, was consumed by the industries producing the chemicals discussed in this report.

The industrial chemicals industry utilizes a large number of processes for producing a wide variety of chemicals. In addition, companies producing the same chemicals may use different processes in manufacturing, depending upon local conditions. It would therefore be impossible to examine every process used for manufacturing every chemical. The chemicals studied are those produced in the greatest quantities based on the assumption that they consume the greatest amounts of energy. Care was taken to note the effects of using fuel as feedstock. The minimum amount of a chemical that must be produced before we considered it here was arbitrarily selected as 4 million tons/yr. However, some chemicals are not produced in such great quantities, but do consume unusually large amounts of energy per unit of production. These select chemicals also have been included here. A list of the chemicals studied is presented in Table 1, with an estimate of their annual production and total energy consumption in 1971 or, in some cases, 1972. These are the latest years for which figures on individual chemicals are available.

Table 1. ANNUAL PRODUCTION AND ENERGY CONSUMPTION OF
SPECIFIC INDUSTRIAL CHEMICALS*

Chemical Group	Chemical	Annual Production	Annual Energy Consumption, 10 ¹² Btu
Alkalies and Chlorines	Chlorine	9,352,437 tons (g) (1971)	285
	Sodium carbonate (syn.)	4,274,763 tons (1971)	161
	Sodium hydroxide	9,666,521 tons (1971)	252
Industrial Gases	Acetylene	11,568 X 10 ⁶ CF (1972)	35.0
	Oxygen	353,000 X 10 ⁶ CF (1972)	15.2
	Hydrogen	58,890 X 10 ⁶ CF (1972)	28.1
	Nitrogen	193,540 X 10 ⁶ CF (1972)	6.6
	Ammonia	14,028,795 tons (1971)	491
Inorganic Chemicals	Aluminum oxide	6,461,978 tons (1971)	82.3
	Ammonium nitrate	6,605,296 tons (1971)	51.1
	Nitric acid	6,742,130 tons (1971)	
	Sulfuric acid	31,300,000 tons (1972)	9.0
	Sulfur	7,868,000 tons (1971)	72.1
	Carbon black	1,508,568 tons (1971)	262.4
	Phosphoric acid	6,240,041 tons (1971)	60
	Methanol	2,474,952 tons (1971)	92.6
Organic Chemicals	Benzene	3,923,408 tons (1971)	
	Toluene	3,152,485 tons (1971)	

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* Including feedstocks.

Alkalies and Chlorine

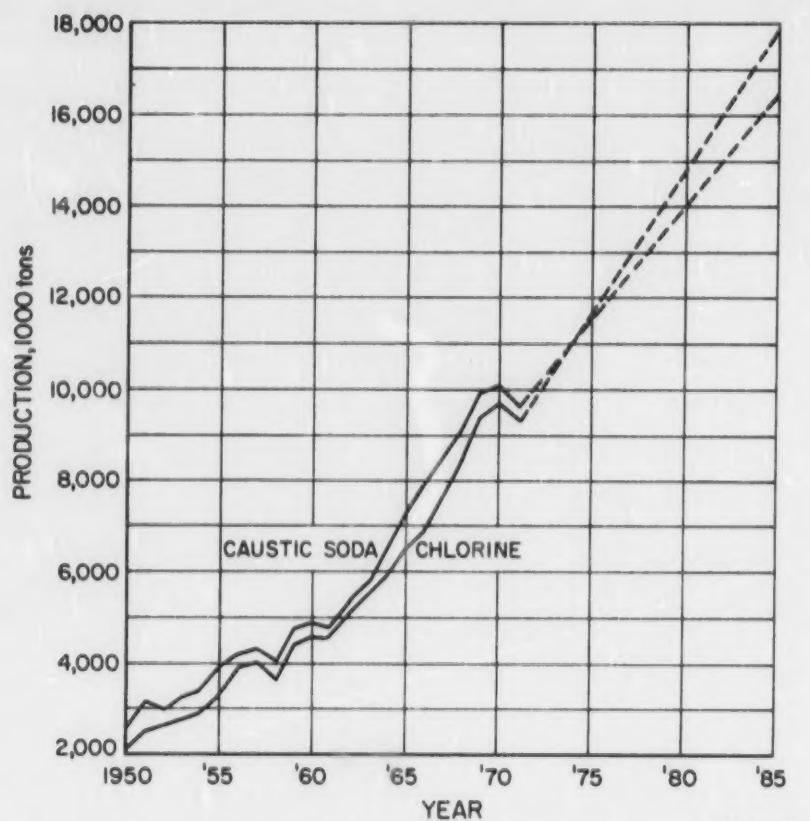
The alkalies and chlorine segment of the industrial chemicals industry produces chemicals such as potassium and sodium carbonates, caustic soda, soda ash, potassium hydroxide, and chlorine. The manufacture of chlorine, soda ash (sodium carbonate), and caustic soda (sodium hydroxide) consumes most of the energy within this group. In 1971, energy consumption in the manufacture of these chemicals is estimated at 446 trillion Btu. Energy consumption is expected to increase to about 595 trillion Btu by 1980.

The demand for these chemicals has been high, resulting in a historical growth rate in production of nearly 9%.¹ Currently, the industry is producing at or very near capacity. This will result in a reduction in growth rate in the future because growth will depend on building new plants to increase capacity. Limited power and fuel supplies also will slow this industry's growth. Finally, natural sources of soda ash are increasing, reducing the need for synthetic soda ash and, in turn, reducing the growth rate slightly. In spite of these conditions, the industry is expected to continue to grow at a rate of 7-8% per year. (See Figure 1.)

Chlorine and Caustic Soda

Chlorine and caustic soda are produced simultaneously by the electrolysis of sodium chloride in either diaphragm cells or mercury cells. One ton of chlorine is produced for every 1.13 tons of sodium hydroxide. In the U.S., the diaphragm cell is used for more than 65% of the total production of these chemicals.⁹ Figures 2 and 3 are flow diagrams of the production of these chemicals using the two types of cells.

In the production of these chemicals, a saturated solution of sodium chloride is steam-heated and then purified by treatment with sodium carbonate and caustic soda. After purification, the solution is neutralized with hydrochloric acid, reheated, and then fed to the electrolytic cells. An electric current is passed through the salt solution, decomposing the salt to form a 10-12% sodium hydroxide solution. In addition, hydrogen gas is formed at the cathode and chlorine gas at the anode.



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Figure 1. ANNUAL PRODUCTION OF CHLORINE AND CAUSTIC SODA WITH PROJECTION TO 1985

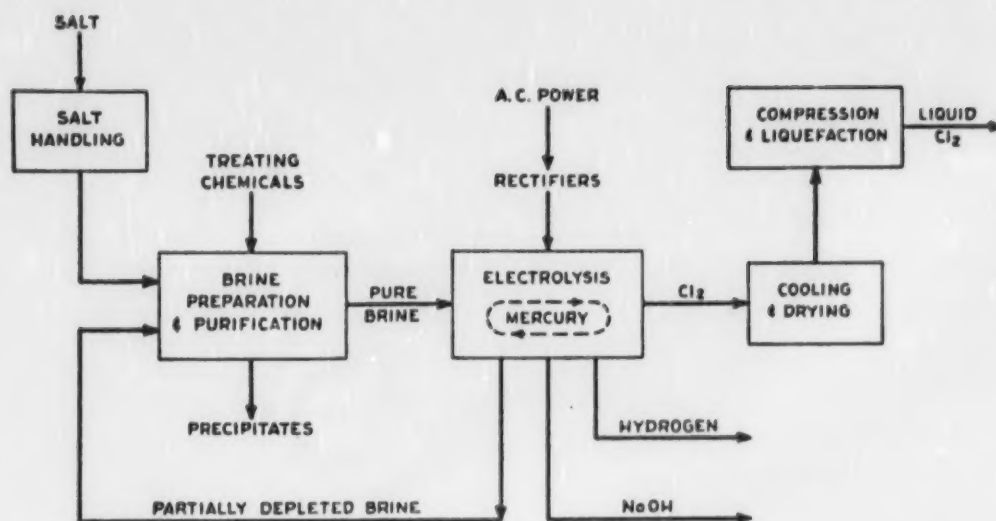


Figure 2. FLOW DIAGRAM OF MERCURY CELL CHLOR-ALKALI PLANT⁹

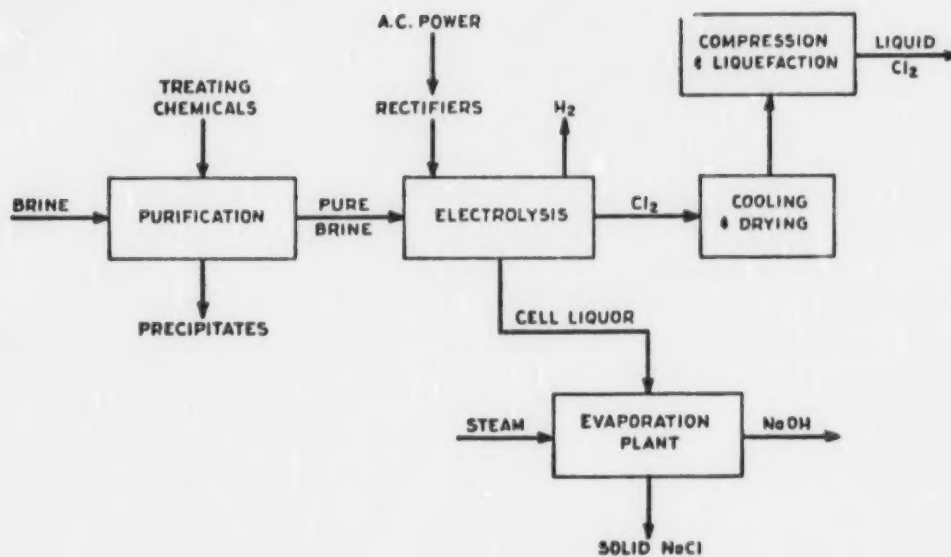


Figure 3. FLOW DIAGRAM OF DIAPHRAGM CELL PROCESS⁹

The amount of energy consumed in the manufacture of these chemicals varies considerably, depending upon the type of cell used. Typically, the diaphragm cell process consumes about 35 million Btu/ton of caustic soda produced, and the mercury cell process consumes only about 12.1 million Btu/ton of caustic soda produced. These are equivalent to 39.5 million Btu/ton of chlorine and 13.7 million Btu/ton of chlorine, respectively.

One difference between these two processes is that the mercury cell actually consumes 15% more electricity than the diaphragm cell (9.4 million Btu/ton of caustic soda versus 8.1 million Btu/ton of caustic soda, respectively). However, the caustic soda solution produced in mercury cells does not need to be concentrated in evaporators, as is the case with the caustic soda produced in diaphragm cells. As a result, the steam required in the mercury cell process is about one-tenth the amount required in the diaphragm process. Note that the figures presented for energy consumed as electricity do not include the energy losses in generation and transmission. At the site of generation, mercury cells consume about 3.9 million Btu more energy than diaphragm cells, but this is still considerably less than the amount of energy that the mercury cell process saves by using so little steam.

The Kel-Chlor Process is a new process for the manufacture of chlorine.¹¹ The process involves oxidation of hydrogen chloride with a catalyst to form chlorine and water. The process consumes very little energy for power or heat; the energy requirements, however, are not known because no commercial-scale plants exist as yet. An additional benefit of this process, from the industry's point of view, is that hydrogen chloride is readily available for feedstock because it is a by-product of a very large number of chlorination reactions. As such, it usually presents a great disposal problem.

Air pollutant emissions from the manufacture of chlorine and caustic soda comprise chlorine gas, carbon dioxide, carbon monoxide, and hydrogen. Mercury vapors also are emitted when mercury cells are used in the electrolysis. About 1.5 lb of mercury is lost for every 100 tons of chlorine produced. Of these emissions, chlorine has been regarded as the most serious, although the mercury emissions are being scrutinized. Hydrogen,

which is one of the by-products of the electrolytic process, is usually collected and either burned elsewhere in the plant or sold. Table 2 summarizes the chlorine emissions and shows that, uncontrolled, chlorine emissions are 60-100% greater for mercury cell plants than for diaphragm cell plants. But Table 2 also indicates, in part, that these emissions can be effectively controlled by scrubbers. Other methods of control include the use of the chlorine in other plant processes and recovery of the chlorine from the effluent gas stream.

Table 2. EMISSION FACTORS FOR CHLOR-ALKALI PLANTS¹⁸

Type of Source	Chlorine gas, lb/100 tons
Liquefaction Blow Gases	
Diaphragm Cell, uncontrolled	2,000 to 10,000
Mercury Cell, * uncontrolled	4,000 to 16,000
Water Absorber	25 to 1,000
Caustic or Lime Scrubber	1
Loading of Chlorine	
Tank Car Vents	450
Storage Tank Vents	1,200
Air-Blowing of Mercury-Cell Brine	500

* Mercury cells lose about 1.5 pounds mercury per 100 tons of chlorine liquefied.

Trends in Chlorine-Caustic Soda Manufacturing

Figure 1 shows the production rates of both chlorine and caustic soda¹⁵ with projections to 1985. Fuel consumption per unit of production for each type of electrolytic cell has remained constant during the last 20 years and will probably continue unchanged in the future. However, total fuel consumption is likely to decrease in the future, in spite of the expected growth in production. One potential factor affecting future energy consumption rates is the possibility of increasing the number of mercury cells in operation. However, the emission of mercury and new water-quality standards threaten to foreclose new mercury cells (as discussed below). But if cleanup of the mercury emissions can be effected, large savings

in energy consumption would result. Figure 4 shows the effect of increasing the number of mercury cells to account for 65% of production rather than the 35% for which they are currently accountable. If this 65% utilization were reached by 1985, the projected annual energy consumption would be reduced by 25%. If mercury cells were used for 100% of production, annual energy consumption in 1985 would be about 14% lower than that in 1971.

The other major factor that could affect the energy consumption of this industry is utilization of the Kel-Chlor Process. Apparently, 100% utilization of this process would reduce energy consumption to almost zero. However, this process is not likely to be in wide enough use by 1985 to have any significant effect on energy utilization patterns.

In addition to their effects on energy consumption, the directions that the industry takes in the future also will affect air pollutant emissions. Growth in the use of mercury cells will significantly increase mercury emissions. At present, mercury losses are about 49,000 lb/yr, based on a 35% utilization of mercury cells. Figure 5 shows the projected effects of mercury cell utilization in the future if a) the current 35% utilization is maintained and if b) utilization increases to 65%. If utilization were to increase to 100%, 270,000 pounds of mercury would be emitted annually. Switching to mercury cells would not affect chlorine emissions because effective cleanup measures exist regardless of the type of cell that is used.

If the Kel-Chlor Process becomes widely used, it is likely to cause a significant increase in emissions of nitrogen compounds (such as, but not exclusively, NO_x), because NO_x are used as the catalyst. Although methods for controlling these emissions are available, data on their effectiveness relative to this process are not.

Sodium Carbonate (Synthetic Soda Ash)

The other major chemical manufactured by the alkalies and chlorine industry is sodium carbonate. There are two sources: natural deposits, from which nearly 2.9 million tons was obtained in 1971, and synthetic manufacturing, which accounted for nearly 4.3 million tons in 1971. Soda ash production in the U.S. has been increasing gradually, and this trend is expected to continue in the future. (See Figure 6.) However, there has

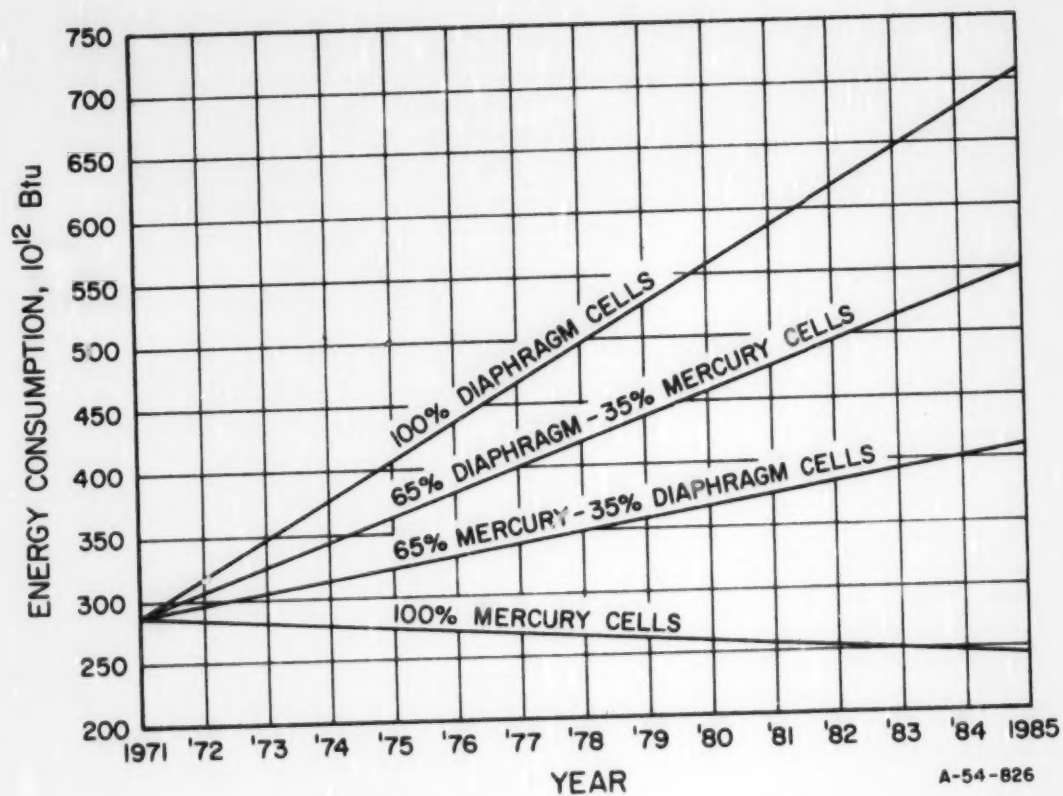


Figure 4. EFFECT OF MERCURY CELL UTILIZATION
ON ANNUAL ENERGY CONSUMPTION OF
CHLORINE-CAUSTIC SODA MANUFACTURE

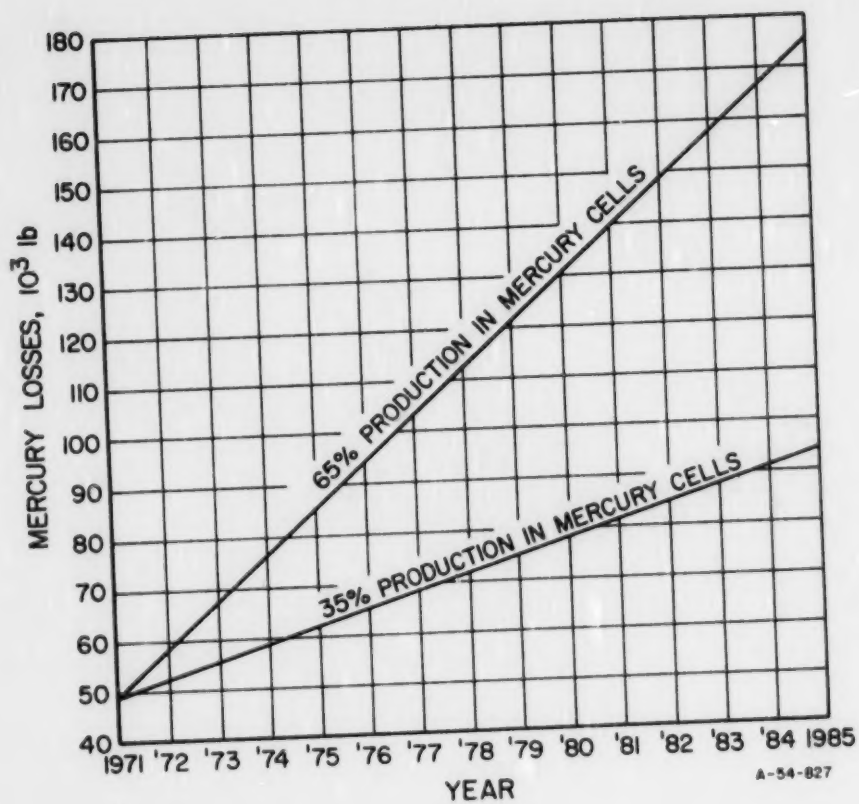


Figure 5. EFFECT OF USING MERCURY CELLS
IN CHLORINE-CAUSTIC SODA MANUFACTURE
ON MERCURY EMISSIONS

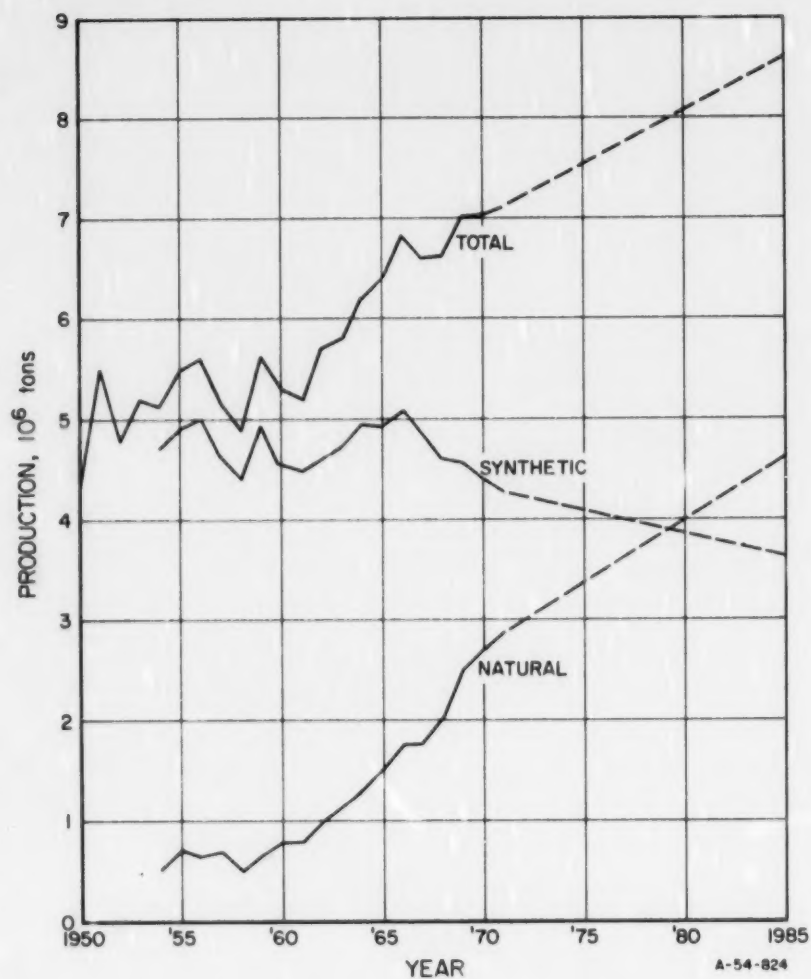


Figure 6. ANNUAL PRODUCTION OF SODA ASH
WITH PROJECTION TO 1985

been a shift away from synthetic soda ash toward natural sources (also shown in Figure 6). As a result, the total energy consumed in the manufacture of this chemical is likely to drop gradually from its 1971 estimated level of 161 trillion Btu/yr.

The primary process for manufacturing soda ash is the Solvay Process.⁶ The first step is purification of saturated salt brine with ammonia and carbon dioxide waste process gases in absorbers. During this step, calcium, magnesium, and other heavy metals are removed. The purified brine is ammoniated and then carbonated to form sodium bicarbonate. The resulting slurry is filtered and then heated to about 350° F in a rotary kiln. The product is cooled and stored or packaged.

Primary consumption of energy occurs in the calcination step, in boilers, and in the lime kilns that produce the calcium carbonate used in the carbonation step. The primary fuel used is coal. However, there has been a trend toward the use of fuel oil in recent years. Energy consumption is estimated to be about 38 million Btu/ton of soda ash produced. Because no new synthetic processes are being developed, the unit energy consumed in this sector is likely to remain unchanged in the near future.

Air pollutants from the manufacture of soda ash comprise primarily ammonia (as shown in Table 3) and dust.

Table 3. EMISSION FACTORS FOR SODA-ASH PLANTS WITHOUT CONTROLS¹⁸

Type of source	Particulates, lb/ton	Ammonia, lb/ton
Ammonia Recovery*	--	7
Conveying, Transferring, Loading, etc.	6	--

* Represents ammonia loss following the recovery system.

The ammonia results from venting the gases from the brine purification system. Additional losses also can be incurred during the transfer of the ammonia from tank trucks to storage tanks. Dust emissions are primarily

the result of handling operations, that is, conveying, transferring, and loading. Some dust also is emitted from the rotary kilns.

Trends in the Manufacture of Soda Ash

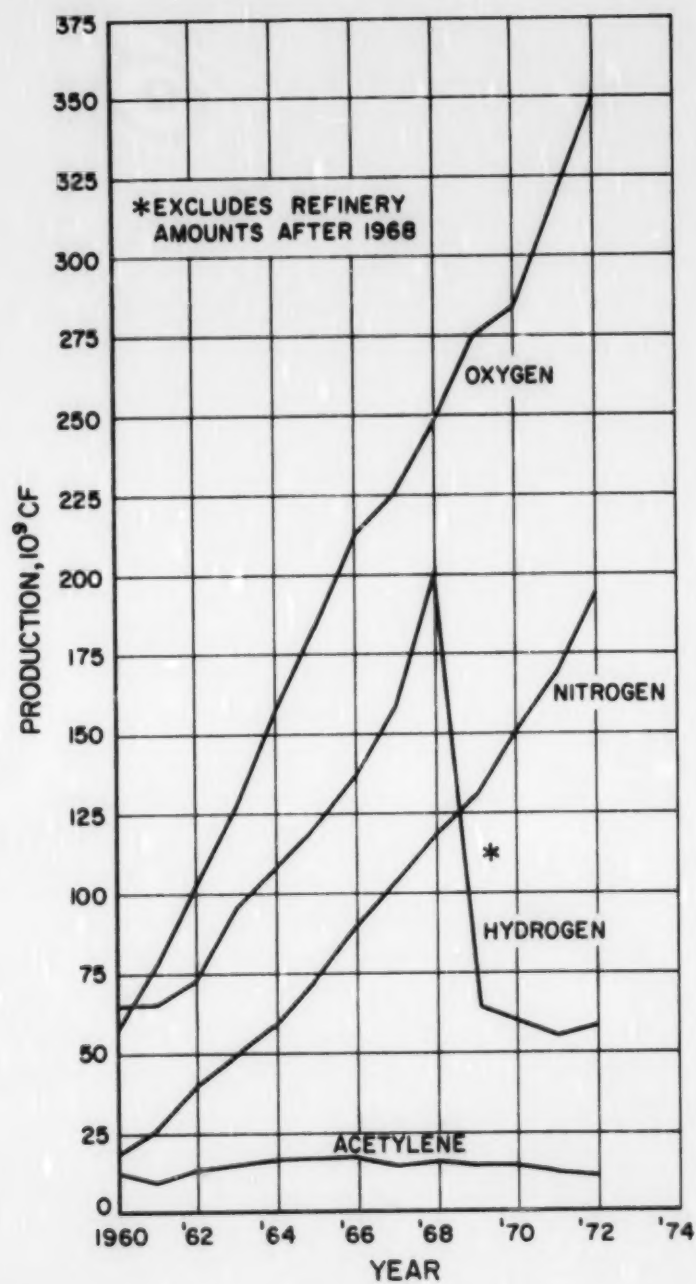
The only change that can be anticipated in this industry is a gradual shift from synthetic soda ash to natural soda ash. At present, more than 80% of the synthetic soda ash production is by the Solvay Process. However, the greater availability of natural soda ash accounts for the shift. In addition, energy consumption is very low* in mining the soda ash — another likely cause for the shift. As a result of this shift, which will be gradual, annual ammonia emissions also will decrease; however, particulate emissions probably will increase.

Industrial Gases

Nine principal gases are produced by the industrial gases segment of the industrial chemicals industry. The gases of most concern are acetylene, hydrogen, nitrogen, and oxygen because they are produced in the greatest abundance of all the industrial gases and consume the major part of the energy consumed by the entire segment. Figure 7 shows the trends in production of these gases since 1960. With the exception of acetylene, the industrial gases presented have exhibited tremendous growth in the last 10 years because the market for these gases has rapidly expanded. At present, industrial gases are the fastest growing segment of the inorganic chemicals industry, primarily because of new techniques in the primary metals industries and the chemical industry. In the U.S., oxygen and nitrogen growth rates have been 19.9 and 26% per year, respectively, since 1960.¹¹ This rapid growth is expected to continue for some time to come.

Energy consumption in 1972 for the production of these gases is estimated at 85 trillion Btu. The sources of energy were primarily natural gas and electricity; however, small amounts of fuel oil and coal, comprising less than 5% of the total energy consumption, were used. The fuels are used for raising steam, for mechanical drives, and for feedstock.

* No actual figures are available.



A-54-830

Figure 7. ANNUAL PRODUCTION OF SELECTED INDUSTRIAL GASES

Acetylene

There are several methods for manufacturing acetylene, but the most commonly used method is by reaction of calcium carbide with water. This reaction is exothermic, releasing about 165 Btu/CF of acetylene produced, and as such does not consume energy. The major amount of energy consumed by this industry is in the production of the reactant, calcium carbide.

To form calcium carbide, lime and coke are mixed in a 6:4 ratio and heated to 3600°-3800°F in an electric furnace. The liquid calcium carbide thus formed is cooled and subsequently solidified. The solid mass is crushed and screened to size, an operation that is carried out in a nitrogen atmosphere to prevent explosion of acetylene that would be generated by moisture in air. The energy consumed to form 1 ton of carbide is approximately 28 million Btu. Approximately 18 million Btu of coke and 10 million Btu of electricity are consumed.⁶ If the energy used to generate the electricity is considered, energy consumption becomes 48 million Btu/ton of calcium carbide produced. Because lime is a major reactant in the formation of calcium carbide, a lime kiln is an integral part of the acetylene plant. Lime kilns typically consume 6-8 million Btu/ton of lime produced. In the reaction of lime with coke, carbon monoxide as well as calcium carbide is formed. The carbon monoxide usually is recovered and used as a fuel in the lime kiln or as a raw material for chemical synthesis.

Acetylene is produced from calcium carbide by one of two processes: the wet process or the dry process. In both processes, calcium carbide is combined with water to form acetylene and calcium hydrate. In the wet process, a large amount of water is used, and the calcium hydrate is discharged in the form of a slurry containing 90% water. In the dry process, a limited amount of water is used, and the heat of reaction is used to dry the calcium hydrate, making it suitable for reuse as a lime source.⁶

There are other processes for manufacturing acetylene utilizing natural gas as a feedstock, including incomplete combustion with oxygen, such as the Sachse Process, and pyrolysis on a hot surface, such as in the Wulff Process. Neither of these processes is economically feasible, and the energy requirements are very high. Natural gas consumption is in

excess of 200 million Btu/ton of acetylene produced. Work is being done to make such processes attractive, but so far the calcium carbide process is the most widely used.

Air pollutant emissions from acetylene-manufacturing plants occur during the manufacture of calcium carbide. Table 4 summarizes these emissions.

Table 4. AIR POLLUTANT EMISSIONS FROM THE
MANUFACTURE OF ACETYLENE¹⁸

<u>Source</u>	<u>Particulates</u>	<u>Sulfur Oxides</u> lb/ton [*]	<u>Acetylene</u>
Electric Furnace			
Hoods	18	- -	- -
Main Stack	20	3	- -
Coke Dryer	2	3	- -
Furnace Room Vents	26	- -	18
Lime Kiln			
Vertical	7.6†	- -	- -
Rotary	190†	- -	- -

^{*}Emissions per ton of calcium carbide produced.

[†]Emissions can be reduced by conventional means by 99%.

In addition, carbon monoxide probably is emitted during the formation of the calcium carbide, and acetylene is emitted from the recovery process during the reaction of calcium carbide and water to form acetylene. However, no data are available on these emissions.

Trends in Acetylene Manufacturing

The manufacture of acetylene has been declining gradually for a number of years, primarily because the chemical industry that previously used large amounts of acetylene for feedstock is switching to other, less hazardous and more available hydrocarbons. This trend is likely to continue in the future, resulting in a gradual reduction in annual energy

consumption and air pollutant emissions. Although other processes exist, they probably will not replace the calcium carbide route.

Oxygen and Nitrogen

The manufacture of oxygen and nitrogen is increasing faster than the manufacture of any other chemical. In 1972, 353 billion CF of oxygen and 194 billion CF of nitrogen were produced,¹⁵ an increase over 1971 of 11% and 15%, respectively. Energy consumed in the manufacture of these gases in 1972 is estimated at 86.8 trillion Btu.

The primary method of manufacture is the same for both of these gases, liquefaction and subsequent fractionation of air. In fact, both gases are produced simultaneously. Several cycles are used to obtain the final product; they all involve the basic processes of air purification, compression, and refrigeration, but the equipment differs. The specifics of the production of these gases are not important, nor is differentiation of the various processes, because the energy consumed is about the same.

The energy consumed in the manufacture of both oxygen and nitrogen is electricity and steam, 22% and 78%, respectively. The amount of energy consumed is 245,000 Btu/1000 CF of oxygen produced, or 60,000 Btu/1000CF of nitrogen produced. However, if the energy consumed to generate the electricity is considered, the actual energy consumption is 3 times as much. The energy is used primarily for mechanical drives.

Air pollutants are not emitted from oxygen or nitrogen plants. If electricity generation is considered, a small amount of emissions can be attributed to the manufacture of oxygen and nitrogen. However, emissions from electricity generation depend upon the source of energy (coal, oil, natural gas, nuclear, etc.). (See the section on electricity and steam generation.) Because we cannot ascertain the combination of fuels that are consumed to generate the electricity specifically used in these industrial gas plants, we cannot attribute quantitative emission numbers to the manufacture of these gases.

No major advances in the processes for manufacturing these two gases have occurred, so it is not likely that any significant changes will alter the energy-consuming characteristics of these industries. Production

of these gases should continue to grow at a great rate. By 1975, annual oxygen production in the U.S. is expected to be 600 billion CF, a 70% increase over 1972 production.⁷ Oxygen, 60% of which is used in the steel industry, is beginning to be used in applications for which higher temperatures, greater productivity, and reduced fuel consumption are desired, such as the glass industry and some nonferrous smelting operations. As fuels become scarcer, this trend is likely to increase, causing even greater growth of this industry. Nitrogen is used as a feedstock in many chemical-manufacturing processes, ammonia-manufacturing being a large user. However, it is becoming widely used as a refrigerant as well; thus, its future growth would seem to be ensured.

Hydrogen

The other major industrial gas produced in large volume and consuming large amounts of energy in the manufacturing process is hydrogen. Figure 7 shows that the annual production of hydrogen totaled 58 billion/CF in 1972. This total does not include hydrogen produced and used in petroleum refineries, which accounts for more than 75% of the total hydrogen produced. Prior to 1969, hydrogen produced in refineries was included in the statistics, thus accounting for the apparent drop in production in 1970 shown in Figure 7. Including the hydrogen produced in refineries, production is estimated to have been about 250 billion/CF in 1972 and is expected to increase to 312 billion CF/yr by 1975.

There are several methods for manufacturing hydrogen, but the most predominantly used method is the catalytic steam reforming of hydrocarbons, including methane, oil refinery gas, liquefied petroleum gas, natural gasoline, naphtha, and fuel oil.¹² In catalytic steam-hydrocarbon reforming, desulfurized feed is mixed with steam and passed over a nickel-based catalyst in a reforming furnace. The effluent gases containing carbon monoxide and hydrogen are cooled with steam or condensate to the point at which the carbon monoxide reacts with the steam to form carbon dioxide and additional hydrogen. The process requires about 450,000 Btu of energy to produce 1000 CF of hydrogen. About half of the energy is consumed as feedstock; the other half is consumed in raising steam.

Other methods of manufacturing hydrogen are dissociation of ammonia, the steam-iron process, and electrolysis of water. The main deterrent to the use of these processes is the high cost of the raw materials and power. Thus, steam-methane reforming probably will dominate in the manufacture of hydrogen in the near future. However, steam-reforming processes that use hydrocarbons other than methane have been developed, and they might replace the steam-methane reforming process when methane becomes scarce.

Specific data on the air pollutant emissions from the manufacture of hydrogen are not available. However, small amounts of methane and hydrogen probably are lost during processing. In addition, emissions occur as a result of the combustion in boilers to raise steam. The emissions, of course, depend on the fuel used. Table 5 summarizes the average emissions from refinery boilers for the two most commonly used fuels.* Some of these emissions, such as NO_x , probably can be reduced by using new combustion techniques that are being developed. In general, these emissions can be controlled by proper treatment of the effluent gases.

One new process for manufacturing hydrogen recently has been developed. This process involves the partial oxidation of hydrocarbons and is said to require less energy for heat than the steam-hydrocarbon reforming process. The energy consumed for heat in this new process is estimated at 35,000 Btu/1000CF of hydrogen produced, which represents an 80% reduction in that required in the steam-hydrocarbon reforming process. In spite of this reduction, this new process is not expected to gain prominence until its economics become favorable. At present, the cost of most liquid hydrocarbons is too high, compared with the cost of present feedstocks, to justify the switch.

A second method for manufacturing hydrogen on a large scale is the electrolysis of water, for which several schemes have been developed.

* For more complete information on boiler emissions, see Section XIV, Electricity and Steam Generation.

Table 5. AVERAGE AIR POLLUTANT EMISSIONS FROM
REFINERY BOILERS USED IN PRODUCTION OF HYDROGEN⁴

Emissions	Unit Emission Rates		1972 Emission Rates	
	Fuel Gas lb/1000 CF H ₂	Fuel Oil	Fuel Gas lb/year	Fuel Oil
NO _x	0.05	0.095	12,700,000	23,800,000
Aldehydes	0.0007	0.0008	175,000	200,000
Hydrocarbons, as hexane	0.0055	0.0048	1,375,000	1,200,000
Organic Acids, as acetic acid	0.0029	0.0154	725,000	3,850,000
Particulate Matter	0.0044	0.0280	1,100,000	7,000,000
SO ₂	*	*	*	*
SO ₃	*	*	*	*

* Sulfur dioxide and sulfur trioxide emissions are dependent upon sulfur in fuel.

The primary objection to this method in the past has been the high cost of electricity; consequently, the target of most of the research has been to reduce electricity consumption to the absolute minimum. Toward this end, a high-temperature cell that uses a zirconia electrolyte^{7,8} has been developed, but as yet has not become economical. Another proposal is the production of hydrogen by electrolysis at nuclear power plants, which would be an economical source of electricity in the future.

Trends in Hydrogen Manufacturing

The consumption of hydrogen is expected to continue to increase as its demand in ammonia-manufacturing, petroleum-refining, and other chemical-manufacturing processes increases. By 1975, hydrogen consumption is expected to increase by 20% over 1972 consumption. Demand for hydrogen probably will increase even more as its potential use as a fuel in industrial and commercial applications is realized. On the current energy requirement basis, energy consumption would be expected to grow linearly with the growth in production. However, if the partial oxidation process becomes widely used, it would have a significant effect on annual energy consumption (Figure 8). Figure 8 assumes a linear growth of the use of partial oxidation to 100% by 1985. Although data on air pollutant emissions from the partial oxidation process do not exist, hydrocarbon emissions could increase over current levels.

A switch to an electrolytic process for manufacturing hydrogen would increase energy consumption if the energy for electricity generation is considered. A perfect electrolytic cell would require about 270,000 Btu of electric energy to produce 1000 CF of hydrogen.⁸ (In practice, the energy consumed is about 540,000 Btu/1000 CF.) At a 30% generation efficiency for electricity, the actual energy consumption is about 1.8 million Btu/1000 CF, 200% greater than the energy required for steam-hydrocarbon reforming. Air pollutant emissions also would be affected, but the degree would depend, of course, on the source of electricity and the cleanup methods employed.

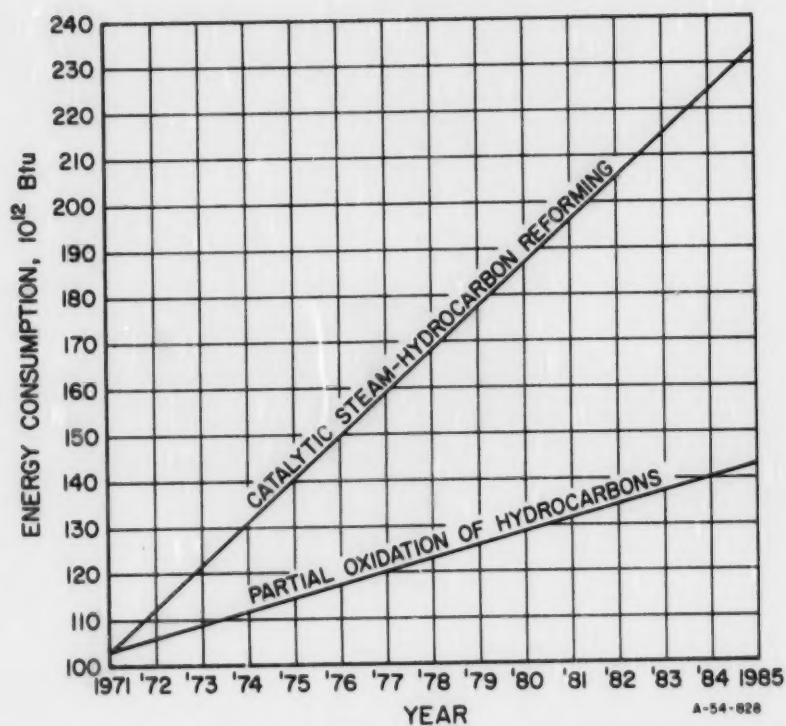


Figure 8. PROJECTED ANNUAL ENERGY CONSUMPTION
IN MANUFACTURE OF HYDROGEN

Industrial Inorganic Chemicals

The industrial inorganic chemicals industry includes establishments engaged in the manufacture of literally hundreds of chemicals. This industry consumes about 26% of the total energy consumed by the industrial chemicals sector of the chemical and allied products sector of industry. In 1971, the total energy consumed is estimated to have been 985 trillion Btu.^{14,16} The majority of the fossil-fuel energy was consumed either in boilers or as feedstock. Only a relatively small amount was consumed in direct-fired processes. As would be expected for such a large diversification of processes, all forms of energy are consumed, although more than half of the energy consumed is electricity. The most important chemicals produced within this sector are shown in Table 1. The manufacture of these chemicals alone accounts for more than 50% of the total energy consumed by the industrial inorganic chemicals sector. Growth of the industrial chemicals industry has been steady, averaging about 10% per year in recent years. The industry output is expected to increase by 50% over current levels by 1980,¹⁷ as will the annual energy consumed by the industry.

Air pollutant emissions from the manufacture of inorganic chemicals also are diverse. Table 6 summarizes the air pollutant emissions from the manufacture of the most important chemicals within this group. As production increases, these emissions will increase, but with an increase in the use of available control methods and hardware, the amount of emissions per unit of production can be reduced.

Ammonia

The manufacture of ammonia consumes more energy annually than the manufacture of any other chemical in this sector. Table 1 shows that, in 1971, more than 14 million tons of ammonia was produced.¹⁵ Of this amount, 80% was used in fertilizers and the rest in industrial and military applications. Although fertilizers are classified separately (SIC Code 287), the U. S. Department of Commerce includes ammonia produced for fertilizer in the inorganic chemicals sector of industry.

Table 6. AIR POLLUTANT EMISSIONS FROM THE MANUFACTURE
OF SPECIFIC INDUSTRIAL INORGANIC CHEMICAL¹⁸

Chemical	Source or Process	Air Pollutant Emissions				
		Particulates	Hydrocarbons	NO _x	SO _x	Carbon
						Monoxide
lb/ton						
Ammonia	Plants with methanator	-	-	-	-	-
	Purge gas	-	90	-	-	Negl
	Storage and load	-	-	-	-	-
	Plants with CO and regeneration systems	-	-	-	-	-
	Regenerator exit	-	-	-	-	200
	Purge gas	-	90	-	-	Negl
	Storage and loading	-	-	-	-	-
						7 3 200
Carbon Black	Channel	2300	11,500 as methane	-	-	33,500
	Thermal	Negl	Negl	-	-	Negl
	Furnace	220	1,800	-	-	5,300
	Gas	60	400	-	-	4,500
	Oil	10		-	-	
	Oil or gas			-	-	385 (H ₂ S)

Ammonia production in the U.S. has been increasing at a rate such that total annual production is currently 3 times as great as in 1960. (See Figure 9.) However, ammonia plants, which rely on natural gas for energy and feedstock, are being restricted because of the shortage of this fuel; consequently, little increase in production is forecast in the near future. Instead, the U.S. is becoming increasingly dependent on foreign sources.¹⁷

The most widely used process for manufacturing ammonia is the catalytic reaction of nitrogen and hydrogen at high temperatures and pressures.^{10,13} The actual manufacture is a series of six consecutive processes incorporated into one plant: 1) reforming of methane with steam to give hydrogen and carbon oxides, 2) secondary reforming of the product gas from step 1 to further reduce its methane content, 3) high-temperature conversion of carbon monoxide to carbon dioxide with shift catalyst, 4) low-temperature shift conversion, 5) methanation, and 6) ammonia synthesis. Energy consumption in an ammonia plant is about 35 million Btu/ton of ammonia produced, including the energy used as a raw material.¹⁰ About 20 million Btu/ton of ammonia produced is consumed as feedstock, 8 million Btu/ton for raising steam, and 7 million Btu/ton as fuel for process heat. For economic reasons, natural gas is the primary source of energy, but if natural gas is unavailable, other sources can be used. In countries where natural gas is not available cheaply, light naphtha from petroleum refineries is used for feedstock. In spite of this, the energy requirements (excluding feedstock) are about the same as those for the process in which natural gas is used. Approximately 3% more energy is required to reform the naphtha than the methane.

Table 6, which summarizes air pollutant emissions from the manufacture of certain inorganic chemicals, shows that carbon monoxide, hydrocarbons, and ammonia are the primary emissions from the manufacture of ammonia. The values given are those for plants without controls. However, through the use of scrubbers, about 99% of the ammonia in the gas streams can be recovered. The carbon monoxide, which makes up about 75% of the regenerator gases, is recovered and burned for fuel when needed, usually for driving compressors.

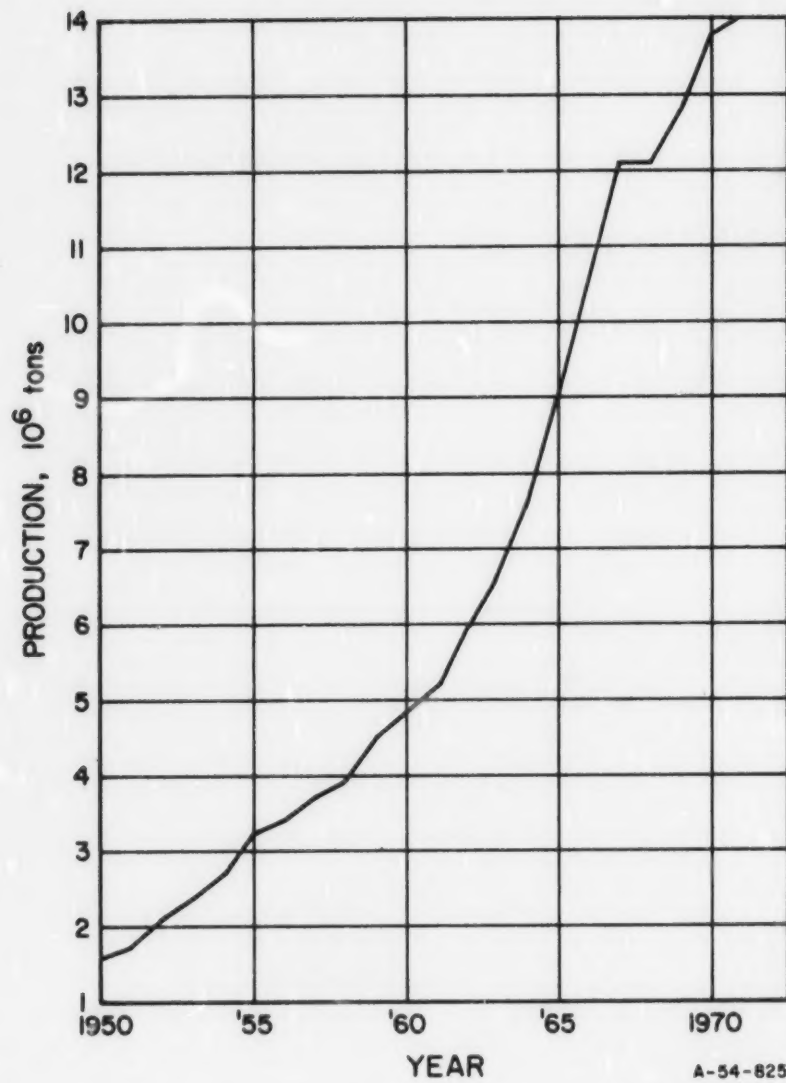


Figure 9. ANNUAL PRODUCTION OF AMMONIA

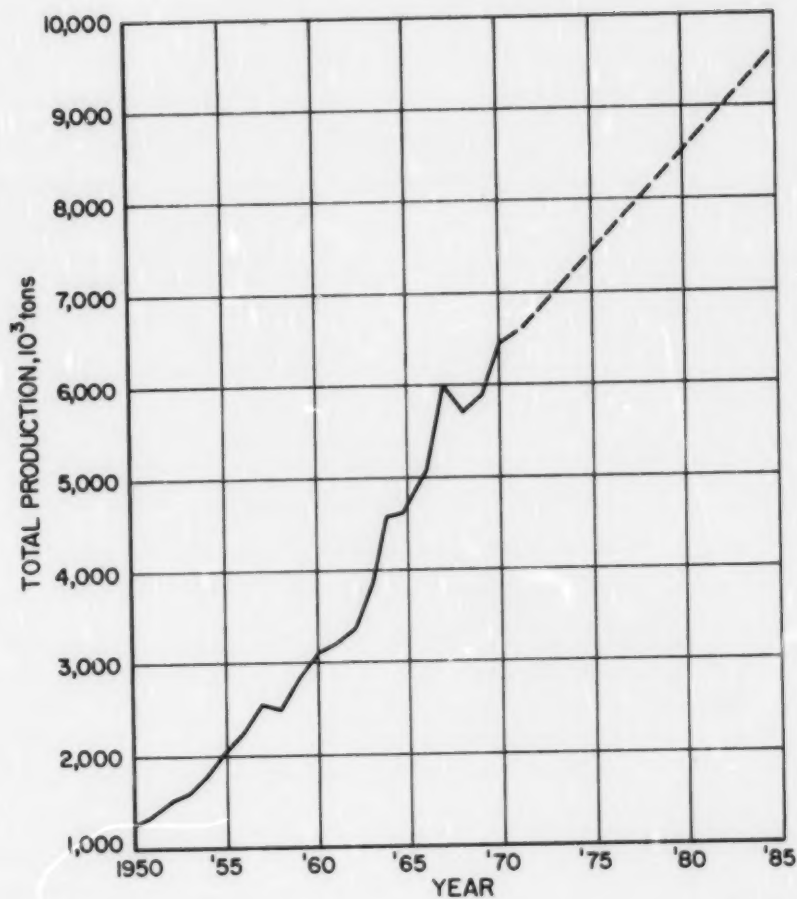
Although no major new processes have been developed for manufacturing ammonia, certain trends have affected the energy consumption pattern of this industry in recent years. Among the most significant developments have been high-pressure reforming, new catalysts, new carbon-dioxide-removal processes, and the use of new feedstock materials. As a result, energy consumption has decreased from about 71 million Btu/ton of ammonia produced with coke or coke-oven gas to the current level of 35 million Btu/ton of ammonia with natural gas. Pressures in the reformer are expected to continue to increase, thus increasing the process efficiency. The trend toward higher pressures should also make partial oxidation of hydrocarbons competitive with reforming as a source of hydrogen. However, the ability of partial oxidation to gain advantage over reforming will depend on the future cost and availability of the various feedstocks.

Ammonium Nitrate

The manufacture of ammonium nitrate consumes about 7.7 million Btu/ton of product. (See Figure 10.) In 1971, approximately 51.1 trillion Btu was consumed to produce about 6.6 million tons. The primary forms of energy used are electricity (10%) and steam (90%),⁶ the fossil-fuel sources of which cannot be determined. (See the section on electricity and steam generation.)

Although there are several variations, depending upon the desired end product, the basic process involves the reaction of ammonia and nitric acid to yield ammonium nitrate. The resulting product then is processed to form crystals or granules.

No information is available on the emissions from the manufacture of ammonium nitrate. However, there are, no doubt, some ammonia emissions. Indirectly, the emissions from the production of ammonia and nitric acid (Table 6) also could be considered, but this would result in a double-counting of emissions because they are considered elsewhere.



A-54-831

Figure 10. ANNUAL PRODUCTION OF AMMONIUM NITRATE
WITH PROJECTION TO 1985

The production of ammonium nitrate is expected to continue to increase at about the same rate as in the past. Thus, annual energy consumption also will increase in proportion to the increase in production. Because the future of ammonium nitrate production depends upon the production of ammonia for use as a reactant, ammonium nitrate production may decline. If this happens, the effect on energy consumption will be directly related to the decline in production.

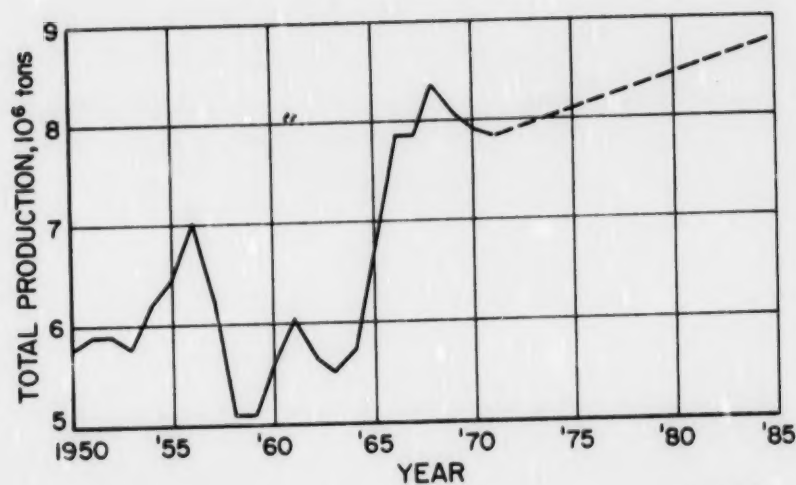
Sulfur

The manufacture of sulfur consumes about 9.1 million Btu/ton of sulfur produced. In 1971, about 72.1 trillion Btu of energy was consumed to produce nearly 8.0 million tons of sulfur.^{6,15}

About 70% of the sulfur consumed in the U.S. is produced by the Frasch Process,² 15% is imported, and the remaining 15% is produced from sour gas and petroleum refinery streams. In the Frasch Process, a well is drilled into a sulfur-bearing deposit, and three stringers of concentric pipe, perforated near the bottom, are lowered to the bottom. Superheated water is pumped into the well to melt the sulfur, which, when molten, settles to the bottom of the well. Compressed air is forced down the innermost pipe and forces the sulfur to the surface through one of the annular spaces.

The majority of the energy consumed in this process is for heating the water. By using heat exchangers, the thermal efficiency is about 80%, leaving little room for improvement. A very small amount of energy is consumed for driving compressors and other mechanical devices. Thus, process energy requirements will probably not change in the near future.

Sulfur production in the U.S. has been increasing at a relatively low rate during the past two decades (Figure 11) and is expected to continue at about the same rate in the future. As a result, total annual energy consumption also will increase from its present level of 72 trillion Btu/yr to about 80 trillion Btu/yr by 1985.



A-54-833

Figure 11. ANNUAL PRODUCTION OF SULFUR BY FRASCH PROCESS

Data on air pollutant emissions from the Frasch Process are not available. However, the emissions can be assumed to be primarily the result of fossil-fuel combustion in the boilers used for superheating the water, including some hydrocarbons, carbon monoxide, NO_x , and SO_x , depending on the sulfur content of the fuel. Because no breakdown of fuel usage by this industry is available, estimates of these emissions cannot be made. (See the section on electricity and steam generation.)

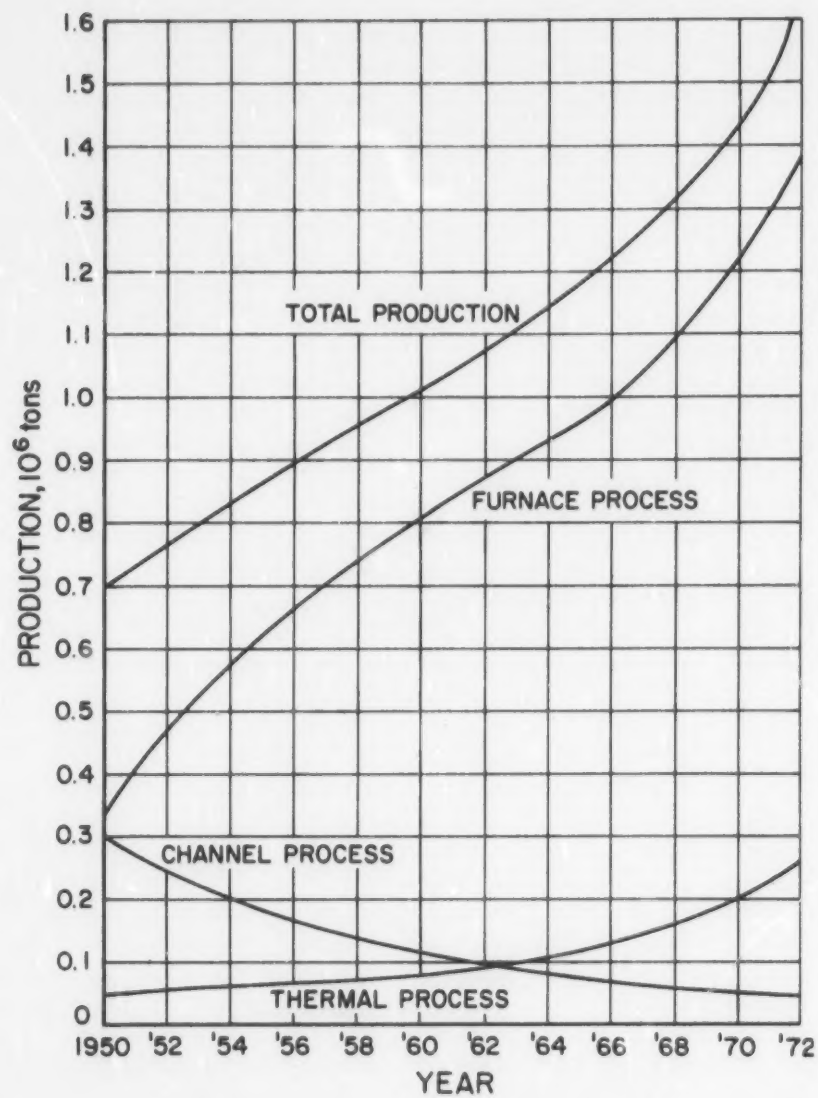
Carbon Black

The carbon-black industry is one of the larger consumers of energy in the industrial chemicals sector of industry. In 1971, carbon-black plants consumed an estimated 262 trillion Btu of energy in the production of 1.5 million tons of product.² The types of energy consumed were primarily natural gas and fuel oil, which are used as feedstock. Air pollutant emissions, although previously a problem, have been significantly reduced; in some plants, reductions of 99.5% have been achieved.³

Carbon black is produced by one of three processes: the furnace process, the channel process, and the thermal process. Figure 12 shows the relative importance of each of these processes on a production basis from 1950 to the present.^{3,5} At present, the furnace process is the most widely used. In this process, fuel is fed into a furnace, in which it is mixed with an amount of air insufficient for complete combustion, resulting in the formation of carbon particles, carbon monoxide, hydrogen, nitrogen, and water vapor. The mixture is cooled, and the carbon-black particles are separated out in an electrostatic precipitator or in cyclone collectors. The feedstock determines the specifics of the plant design. Fuel oil is used as feedstock for about 75% of the total carbon black produced by this process.²

The channel process, which used to account for more than 90% of the carbon black produced in this country, now accounts for less than 5%. This process is similar to the furnace process in that the mechanism of production is incomplete combustion of natural gas. However, many small flames are used, as opposed to one big flame in the furnace process, and the carbon black is deposited by impingement upon the flat undersurface of moving channels. It is removed from the channels by a series of scrapers and collected for packaging. When the furnace burns natural gas only, the yield of carbon black is about 2.5 lb/1000 CF of gas, about one-third the yield of the furnace process.⁵ Some producers that still use this process enrich the gas with oil and thus raise the yield over that available with gas alone.

In the relatively new thermal process, carbon black is produced by thermal decomposition of natural gas rather than incomplete combustion. At present, this process accounts for perhaps 15% of the total carbon-black production. Unlike the other two processes, energy is consumed not only as feedstock, but also as a source of heat for the decomposition. Operating temperatures range from 2400° to 2800°F, and the yield is about 16 lb/1000 CF of gas. Although this yield is significantly higher than that



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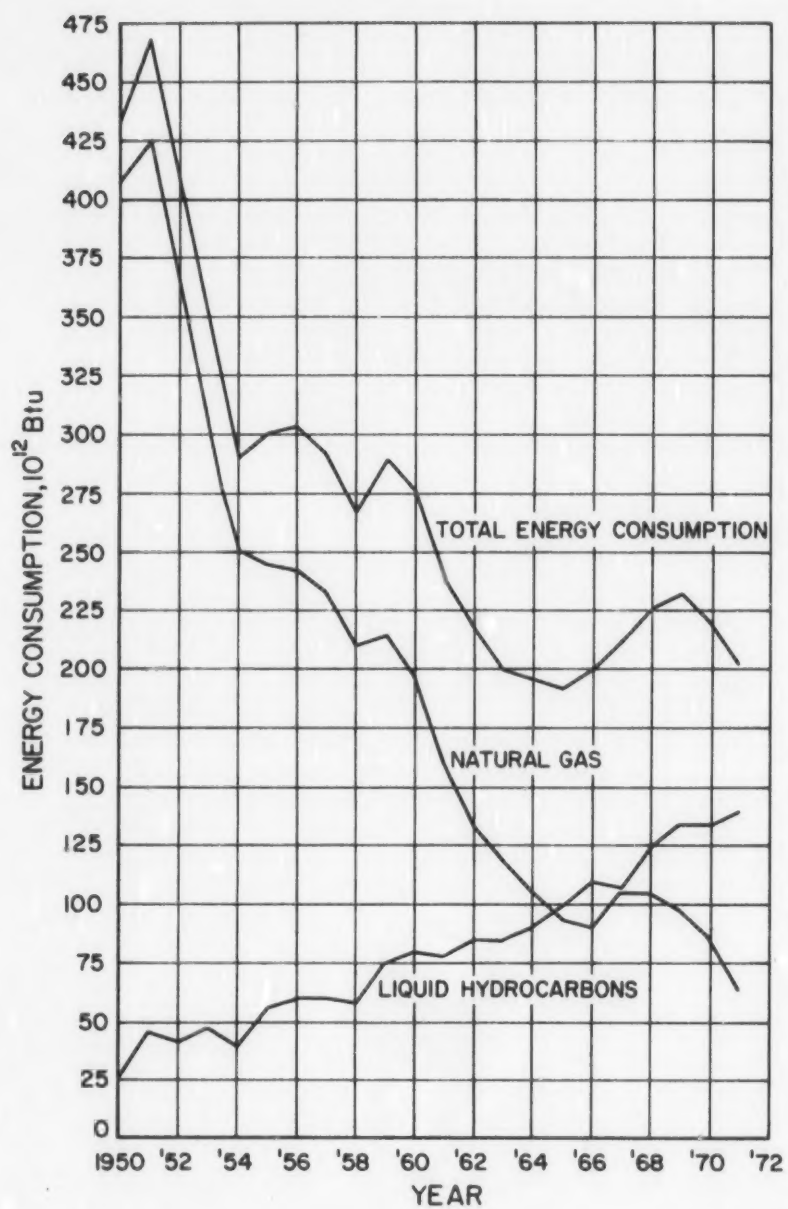
Figure 12. CARBON-BLACK PRODUCTION BY PROCESS
IN THE U.S.

from the channel process, the coarser particles that are produced have neither the reinforcing properties nor the color of channel black.⁵

Figure 13 summarizes the energy utilization patterns of this industry since 1950. The data show a large reduction in energy consumption (and natural gas consumption) between 1950 and 1954, continuing at a lesser rate after 1954. This reduction is a result of the conversion of the industry from the utilization of the inefficient channel process to the much more efficient furnace process. The data also show that liquid hydrocarbons are assuming the burden as primary feedstocks in the furnace process because the carbon black yield per million Btu consumed in the furnace process is 2 to 3 times greater when using liquid hydrocarbons than when using natural gas.

Air pollutant emissions have been a problem for the carbon-black industry for a number of years. In fact, one reason for the conversion from the channel process to the furnace process was the fewer air pollutant emissions from the furnace process. (See Table 6.) The data also indicate that emissions from an oil-fired furnace are lower than those from a gas-fired furnace. The only exception is hydrogen sulfide, the emission rate of which depends upon the sulfur content of the fuel. Finally, the data show that emissions from the thermal process are negligible. The reason is that the exit gases, which are primarily hydrogen (85%), methane (5%), and nitrogen, are either recycled to process burners or used in boilers to generate steam.

The pollution problems of a carbon-black plant can be solved in several ways, including recycling the carbon monoxide and hydrocarbons and burning them elsewhere in the plant, as is done in plants using the thermal process. The use of a fabric filter system is 99.5% efficient in cleaning up particulates. Less efficient cleanup systems such as cyclones and scrubbers also are in use. Efficiencies of these systems range from 90 to 97%, depending upon the specific combinations used. If the whole industry used the fabric filter system, particulate emissions in 1971 would have been about 7500 tons. No information is available on the actual amount of particulate emissions in 1971.



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Figure 13. ANNUAL ENERGY CONSUMED IN THE
MANUFACTURE OF CARBON BLACK

Trends in Carbon-Black Production

By 1980, carbon-black production is expected to increase by 60% or more over 1971 production to an estimated 2.4 million tons. On this basis, the total annual energy consumption will be about 417 trillion Btu, based on an average unit fuel consumption of 173 million Btu/ton. In recent years, the trend has been toward liquid hydrocarbon feedstocks in the furnace process. Because the yield of carbon black per million Btu of energy consumed is highest for this process, its growth, in view of the shortages of other feedstocks, is virtually ensured. In addition, carbon black from oil is superior in quality to carbon black from gas, and the liquid hydrocarbon feedstock is cheaper than natural gas. Liquid hydrocarbons will be used to produce an estimated 85% of the total carbon black produced by 1985, barring any unforeseen changes. The effect of this trend on air pollutant emissions will be minimal if adequate cleanup procedures are used. However, as more oil is used, adequate measures for controlling hydrogen sulfide emissions (not a problem with natural gas) will have to be taken either in the form of cleanup or in the form of removing sulfur from the fuel prior to feeding it into the furnace.

Phosphoric Acid

The manufacture of phosphoric acid requires from 0.5 million to 25 million Btu/ton of acid, depending upon which one of three processes is used. In 1971, 6.25 million tons of phosphoric acid was manufactured in the U.S.¹⁵ Energy consumed by this industry is estimated at 60 trillion Btu.

The most widely used process for manufacturing phosphoric acid is the wet process, in which sulfuric acid is reacted with phosphate rock to produce the acid. The solution resulting from this reaction is separated from the gypsum, which also is formed as a precipitate, and then concentrated by evaporation. The entire process consumes about 0.5 million Btu/ton of acid produced, primarily for mechanical operations and in boilers. Based on an estimate of 4.0 million tons of acid produced in this manner, 2.0 trillion Btu of energy was consumed in 1971.⁶

The process that used the majority of the energy consumed by this industry but only produced about 1.3 million tons of acid was the electric-arc furnace process ("two-step thermal process"). In this process, phosphate rock is reduced to elemental phosphorus by the action of coke and heat in the presence of sand and subsequently oxidized by air to phosphorus pentoxide. The phosphorus pentoxide then is hydrated to form the acid. The energy required by this process is about 25 million Btu/ton of acid produced.⁶ The energy is used as electricity to supply the necessary heat for breakdown of the rock to phosphorus. Energy also is used as coke. This process consumes approximately 14 million Btu of electricity and 11 million Btu of coke per ton of acid produced.

The third process for manufacturing phosphoric acid is actually a "one-step" version of the thermal process previously described. In this process, molten phosphorus is sprayed into a combustion chamber along with air and steam. The reaction produces phosphorus pentoxide, which then is hydrated to form the acid. The process is used where phosphate rock is not available for conversion to phosphorus. The primary use of energy in this process is for steam generation; the amount of steam used varies considerably. Approximately 900,000 tons of acid was produced by this process in 1971.

Air pollutant emissions from wet-process phosphoric acid manufacture consist of rock dust, fluoride gases, particulate fluoride, and phosphoric acid mist, depending upon the design and condition of the plant. (See Table 6.) In the thermal process (electric furnace and phosphorus burning), the primary emission is phosphorus pentoxide acid mist. However, most plants are equipped with cleanup devices, the relative effects of which are shown in Table 6.

Emissions from the wet process, shown as uncontrolled in Table 6, are controllable. Vapor scrubbers are universally employed to control fluoride emissions. Such devices include venturi scrubbers, impingement scrubbers, and various spray towers. These devices are capable of reducing emissions up to 99%. Thus, whereas total fluoride emissions from uncontrolled wet process plants would be about 156 million lb/yr, total emissions from effectively controlled plants would be about 1.6 million lb/yr. This number can be expected to increase as production increases.

Trends in Phosphoric Acid Manufacture

In recent years, the technology of phosphoric acid manufacture has undergone several changes. First, there was a shift from the wet process to the electric furnace process, which produces a purer product, followed by shifts in plant sites due to the development of phosphate rock deposits. Second, as plant equipment improved, there was a rebirth of the wet process. As a result of these changes, all processes are in use today. The wet process predominates, however, and it will probably remain predominant because of fertilizer requirements. Because this process consumes virtually no energy, total energy consumed per year by this industry will probably decrease. Also, several investigations are under way to change the reactants within the wet process from sulfuric acid to hydrochloric acid. However, if this change actually takes place, it will affect neither the energy requirements of the process nor the pollutant emissions.

Other Inorganic Chemicals

Two chemicals are produced in excess of 4.0 million tons/yr, shown in Table 1, but, as it turns out, they are not large consumers of energy: nitric acid and sulfuric acid. In nitric-acid production, the primary reaction is the oxidation of ammonia, the products of which are passed through a catalyst to form NO_x . These, in turn, are hydrated to form the acid. The heat of reaction of ammonia and oxygen is used as the source of heat required in other phases of the process. The manufacture of sulfuric acid is similar. In this case, most of the process heat is obtained from the heat of combustion of sulfur.

The only other chemical presented in Table 1 but not previously discussed is aluminum oxide. Discussion of the manufacture of this chemical is not presented here because this information is given in the section of this report on aluminum manufacturing. Most of the 6.4 million tons of aluminum oxide produced is used in the manufacture of aluminum.

Industrial Organic Chemicals

The industrial organic chemicals industry is a heavy user of fossil fuels because all the chemicals produced are hydrocarbon-based. Most of the fossil fuel is used for feedstock; only a small percentage is used for process heat. Electricity supplies what little energy is required for mechanical drives. As a result, it is difficult to believe that the energy required per unit of production by this industry will change very much. As production increases, so too will total energy consumption. Although the manufacture of all these chemicals consumes large amounts of energy, three chemicals within this group — methanol, benzene, and toluene — stand out as exceptionally large consumers because of their high annual production relative to others within this group.

Methanol

Methanol is produced by the reaction of hydrogen and carbon monoxide under high pressures. Although there are a number of ways to obtain the reactants, the most common way in the U.S. is by reforming natural gas. For every ton of methanol produced, about 28 million Btu of natural gas is reformed to supply the reactants.⁶ Additional energy is consumed for process heating. In 1971, nearly 93 trillion Btu of energy, primarily natural gas, was consumed in the production of 2.47 million tons of methanol. The chief outlet for methanol is in the manufacture of formaldehyde, which is expected to increase in the future. However, if the methanol-based fuel cell were to become an economic reality, a drastic increase in methanol production would result.

In the production of methanol, carbon monoxide and hydrogen are mixed (1:2), compressed to pressures of 3000-5000 psi, and heated in heat exchangers by the product gases. The heated gases pass through a catalytic converter, which must be cooled to maintain a temperature of about 550° F. The methanol-containing gases leaving the converter are cooled and condensed to liquid methanol. Further purification, if desired, is accomplished by distillation.

As previously stated, the primary source of the reactants is the reforming of natural gas. However, there are other sources. Hydrogen is sometimes obtained by electrolysis, and carbon monoxide is sometimes obtained from by-product gases from calcium carbide furnaces. Other sources, which produce both hydrogen and carbon monoxide in roughly equal proportions, are fermentation by-product gases and the manufacture of coke and blue-water gas from coal and water. In spite of these other sources, natural gas is still the primary feedstock. Process heat requirements are generally fulfilled by utilizing the heat of reaction of carbon monoxide and hydrogen.

There is no specific information on the air pollutant emissions from a methanol plant other than for the reforming of natural gas. (See the discussion of ammonia production.) However, it would be reasonable to assume that some carbon monoxide, some hydrogen, and some hydrocarbons are emitted during the manufacturing processes. If methanol production increases, then so too will the total annual emissions, but air pollutant emissions per unit of methanol produced are not likely to decrease because no new processes that could affect them are anticipated.

Benzene and Toluene

Benzene is one of the most abundantly produced organic chemicals in the U.S. In 1971, approximately 3.9 million tons was produced. Benzene can be produced from the destructive distillation of coal, from the dehydrogenation of selected petroleum stocks, and from the hydrodealkylation of toluene. Whereas coal distillation was the only method of production before World War II, hydrodealkylation is the primary manufacturing process today.

In this process, toluene and occasionally xylene are reacted with hydrogen to produce benzene and methane. There are several ways in which this reaction is carried out, both catalytic and thermal. Typically, toluene and hydrogen are mixed and preheated to 1000° - 1200° F and fed to the dealkylation reactor. The products then are fed to a flash drum, where pressure is reduced and hydrogen removed and recycled. The remaining products go into a stabilizer, where fuel gas is removed. The products are cooled, and the liquid product from the stabilizer then is distilled to

yield benzene. Most of the energy consumed by this process is for feedstock. Approximately 2500 pounds of toluene and about 55 pounds of hydrogen are required to produce 1 ton of benzene.⁶ Figures for other energy requirements are not available.

Because toluene is the major feedstock for benzene production, the energy required to produce this chemical should be added to the energy required for benzene production. However, no quantitative data on this subject have been found. Although naphthenes are used as feedstock, the amount of naphthene used depends upon its quality. The primary process for manufacturing toluene is the catalytic dehydrogenation of the naphthenes in the presence of hydrogen, which yields a mixture of aromatic hydrocarbons, chiefly toluene.

Although benzene and toluene are classified as organic chemicals, production occurs primarily in petroleum refineries. Thus, no specific data on air pollutant emissions from the manufacture of these chemicals are available. A general discussion of air pollutant emissions from refineries is presented in the section on petroleum refineries.

Trends in Benzene and Toluene Manufacture

The annual production of benzene and toluene will continue to grow in the future. Benzene is a primary feedstock for a number of chemicals, including styrene, phenol, and nylon via cyclohexane. Toluene is used in gasoline and in the production of benzene. Several processes are used for manufacturing these chemicals, but the ones described above are the most widely used. Barring any great shortage of raw materials, these processes probably will remain the most important. If a shortage does develop, the industry could revert to coal, but the amount of coal required to maintain reasonable production rates would be large. For benzene alone, 1 ton of coal is required to produce about 2 gallons of benzene. Based on 1971 production figures, more than 500 million tons of coal, or 13,000 trillion Btu of energy, was consumed. The effect on air pollutant emissions also would be great because the process is basically that of producing coke. (See the discussion of coke ovens in the steel section.)

Conclusions

There is undoubtedly some room for reducing energy consumption per unit of production within the industrial chemicals industry, but the amount that can be expected is not great. About 55% of the energy consumed by this industry is for process heat, most of it as steam. The remaining 45% is consumed for mechanical drives and feedstock, mainly the latter. With these facts, large savings of energy are not conceivable.

For the air pollutant emissions of this industry, the major emphasis should be on control. Because most of the fuel is used by this industry in boilers, changes in the type of fuel used will alter the emission characteristics. However, the effect of such changes cannot be determined without an accurate assessment of emissions at present. (For a more complete discussion, see the section on electricity and steam generation.) Similarly, changes in electricity consumption will alter emissions, but only at the source of electricity. Emissions directly attributable to specific processes are numerous as are the methods of control. However, good maintenance and usage of available control equipment should ensure minimum emissions in the future.

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IV. SIC CODE 282 - PLASTICS MATERIALS AND SYNTHETICS

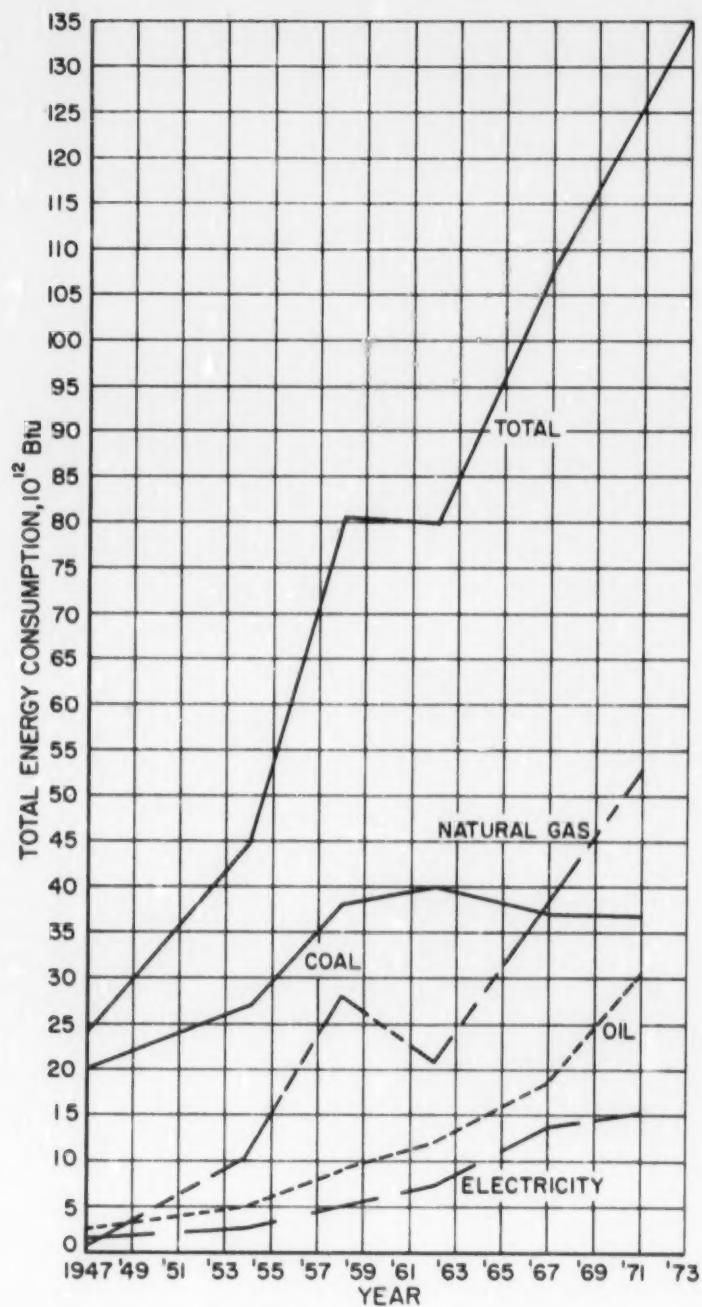
Summary

SIC Code 282 includes chemical establishments primarily engaged in manufacturing plastics materials and synthetic resins, synthetic rubbers, and cellulosic and man-made organic fibers. Establishments that manufacture rubber products and that compound purchased resins or fabricate plastic sheets, rods, or other plastic products are not included within this group.

The plastics materials and synthetics industry consumes more than 3.5% of the total energy consumed by industry in the U.S., excluding fossil fuels consumed as feedstock.⁶ The most important industry segment within this classification is plastics materials and resins, because plants within this segment consume the greatest portion of energy and manufacture the most abundantly produced plastics: polyethylene (3.2 million tons in 1971), polystyrene (1.6 million tons in 1971), and polyvinyl chloride (1.7 million tons in 1971).⁸ The energy consumed by this industry in 1971 was 134 trillion Btu, excluding feedstock; 38.9% of the total energy consumed was natural gas, 27.2% was coal, 22.7% was oil, and 11.2% was electricity.⁶ (See Figure 1.)

Because plastics are a hydrocarbon-based product, much of the fossil fuel consumed by this industry is consumed as feedstock after having been converted to the primary raw materials actually used by this industry. These primary materials are ethylene, styrene, and vinyl chloride, all of which require fossil fuels (natural gas, fuel oil, and coal) for manufacture. Even though the plastics industry does not actually produce the raw materials, the fuels consumed in their production should be considered when analyzing this industry. Table 1 summarizes the consumption of these primary materials in 1967, the most recent year for which this information is available.

Most of the energy consumed in the manufacture of the raw materials is consumed as feedstock, which, in turn, also was manufactured. That is, one chemical is produced for feedstock in the manufacture of a second chemical, which is then used in the manufacture of a third chemical, and so on. Thus, it is not realistic to consider the energy consumed in the manufacture of



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Figure 1. TOTAL ANNUAL ENERGY CONSUMPTION OF PLASTICS MATERIALS AND RESINS INDUSTRY

Table 1. SPECIFIC MATERIALS CONSUMED IN THE MANUFACTURE OF PLASTICS MATERIALS AND RESINS IN 1967 (Ref. 5)

<u>Material</u>	<u>Amount Consumed, 10⁶ tons</u>	<u>Energy Consumed in Manufacture, 10¹² Btu^a</u>
Ethylene	1.02	38.7 ^b
Styrene	0.78	-- ^c
Vinyl Chloride	0.73	-- ^d

^a Not including feedstock.

^b Feedstock is refinery gas made up of a mixture of hydrocarbons.

^c Most of the energy consumed is benzene (1730 lb/ton) and ethylene (6401 lb/ton) consumed as feedstock.

^d Most of the energy consumed is acetylene and ethylene consumed as feedstock.

the third chemical. But it is important to realize that this practice does go on within this industry.

Resin-Manufacturing Processes³

The chemical conversion process used for resin manufacture is polymerization, in which simple molecules react to form polymers. Two principal types of polymerization reactions exist: condensation and addition. A condensation process reacts pairs of chemical function groups to form a group not present in the reactants and splits out water. An addition process opens a chemical bond in a reactant and forms similar bonds with other reactants without the formation of side products.

Polymerization occurs in a number of ways, namely, bulk, solution, emulsion, or suspension. Bulk polymerization is carried out in either a gas or liquid state, but it is difficult to achieve on a large scale. Polymerization of gaseous monomer is likely to result in a low yield without the aid of high operating pressures or a catalyst. Addition polymerizations are exothermic; thus, evolved heat is removed to control the reaction. Solution polymerization is conducted in a solvent that is suitable for both the monomer and the reaction initiator. The polymer may remain in solution or separate. In suspension polymerization, the monomer is suspended in water by agitation. Talc or bentonite is added to stabilize the suspension and prevent polymer globules from adhering to each other.

Emulsion polymerization differs from suspension polymerization in that soap is added to stabilize the monomer droplets and form aggregates called micelles. These micelles take the monomer into their interior, and the initiator dissolved in the aqueous phase diffuses into the micelle to start polymer growth. At certain degrees of polymerization, the polymer is ejected from the micelle, but continues to grow, and the monomer diffuses back into the micelle to replenish it. Emulsion polymerizations are rapid and can be carried out at relatively low temperatures.

Polyethylene⁴

The three basic processes for producing polyethylene are as follows:

1. The high-pressure or Imperial Chemicals Industries (I. C. I.) Process
2. The medium-pressure Phillips Petroleum Process
3. The low-pressure Ziegler Process.

The I. C. I. Process is used to produce low-density polyethylene, and the Phillips and Ziegler processes are used to produce high-density polyethylene.

In the I. C. I. Process, ethylene is passed over heated copper to remove oxygen and then compressed to as much as 500 atm of pressure. A catalyst is added, along with a chain modifier, before compression and polymerization begin. The reaction is exothermic, and temperatures are maintained at 400°F. Upon completion of the reaction, the polymer is extruded as a ribbon, cooled, and then granulated.

In the Phillips and Ziegler processes, gaseous ethylene is fed into a hydrocarbon solvent containing a catalyst. In the Phillips Process, the catalyst is partially reduced chromium oxide supported on activated silica or alumina. In the Ziegler Process, the catalyst is a mixed metal alkyl/metal halide. In the Phillips Process, polymerization occurs at about 500 psi and 350°F, whereas in the Ziegler Process polymerization occurs at or lightly above atmospheric pressure and at temperatures of 125°-150°F. The slurry that results from both of these processes is freed from solvent and washed to remove catalyst residues.

Polystyrene⁴

Polystyrene is manufactured by any of several available processes, depending upon the qualities desired in the end product. The main commercial

processes are bulk polymerization, solution polymerization, and suspension polymerization. In all these processes, a reaction medium, such as a solvent, is used, and in solution and suspension polymerization, a catalyst also is used to promote the reaction. Styrene, the feedstock, is produced by reacting ethylene with benzene in the presence of a catalyst to produce ethyl benzene. The ethyl benzene undergoes dehydrogenation to yield styrene.

Polyvinyl Chloride⁴

Polyvinyl chloride is produced by the bulk, solution, suspension, or emulsion polymerization of vinyl chloride. The most commonly used are the suspension and emulsion methods. In suspension polymerization, water-soluble suspension agents and an initiator are mixed with the monomer, stirred to maintain a suspension, and heated to about 125°F to effect polymerization. Emulsion polymerization is similar, except that an emulsifying agent is used, the initiator system is initially contained in the water phase, and the product obtained is much finer in particle size. Manufacture of the monomer consumes acetylene or ethylene as feedstock, depending upon the process used.

Energy Utilization Pattern

Several possible polymerization reactions lead to the production of the resins discussed above, so precise data on energy utilization applicable to the manufacture of each resin are not available. Examination of the small amount of data that are available indicates a wide range of consumption rates. For example, the energy required to produce 1 ton of polyethylene varies from 1.4 million to 7.0 million Btu, exclusive of feedstock.² In most cases, the energy is consumed as steam and electricity for process heat and mechanical drives. Energy consumed to produce 1 ton of polystyrene also varies, but, according to one source, is about 3.5 million Btu.¹ Energy consumption statistics concerning polyvinyl chloride manufacture are not available.

Air Pollutant Emissions

The major sources of emissions from plastics manufacturing are the reaction vessels. During polymerization, monomers, solvents, and other volatile materials are emitted. However, most of these emissions are well

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Air Pollutant Emissions

The major sources of emissions from plastics manufacturing are the reaction vessels. During polymerization, monomers, solvents, and other volatile materials are emitted. However, most of these emissions are well

controlled because they are recycled into the process on a routine basis. The controls for this purpose include vapor recovery systems, purge lines that vent to a flare system, and vacuum exhaust line recovery systems. Emissions from the production of plastics without controls are shown in Table 2.

Table 2. EMISSIONS FROM THE MANUFACTURE OF PLASTIC MATERIALS WITHOUT CONTROLS⁷

<u>Type of Plastic</u>	<u>Particulate</u>	<u>lb/ton</u>	<u>Gases</u>
Polyvinyl Chloride	35		17
General	5-10		--

Particulate emissions are generally controllable with fabric filters, which have a 98-99% collection efficiency.

Trends in Plastics Manufacture

The plastics industry is one of the fastest growing industries, increasing production at an estimated 13% per year. This growth is likely to continue, but at a reduced rate of about 8% per year, because raw materials are already in short supply, as are the fuels required to produce them, and this shortage is expected to continue for several years. Although new processes and new plastics are being developed all the time, there is no clear information regarding their effects on the industry.

However, based on the number of processes currently in use, new processes requiring less energy will be developed. In addition, as fuel costs increase, more efficient utilization of waste heat, such as the exothermic heat of reaction, will occur. Changes that will affect the short-term energy consumption patterns of this industry are not likely to occur. By 1980, energy consumption will be about 400 trillion Btu, excluding feedstock, 3 times the consumption rate in 1971.

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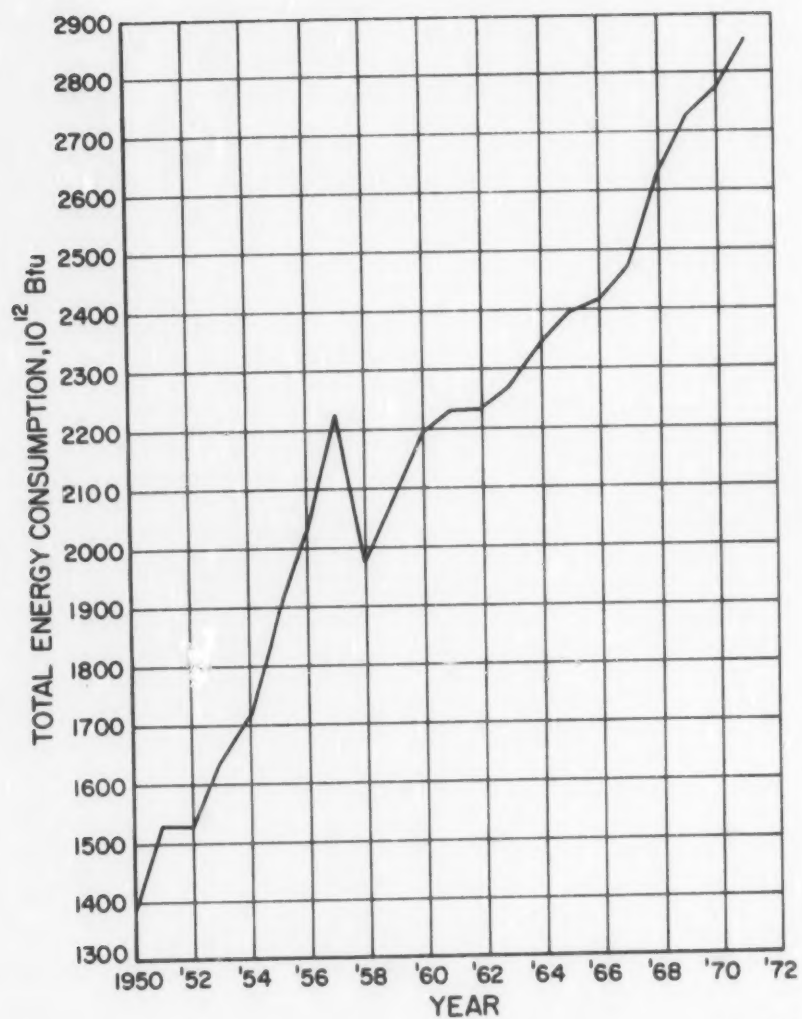
V. SIC CODE 291 - PETROLEUM REFINING

Summary

The petroleum-refining industry includes establishments primarily engaged in the refining of crude oil to produce gasoline, kerosene, distillate fuel oils, residual fuel oils, and lubricants. Establishments that produce natural gasoline from natural gas, establishments that produce lubricating oils and greases by blending and compounding purchased materials, and establishments that re-refine used lubricating products are classified elsewhere.

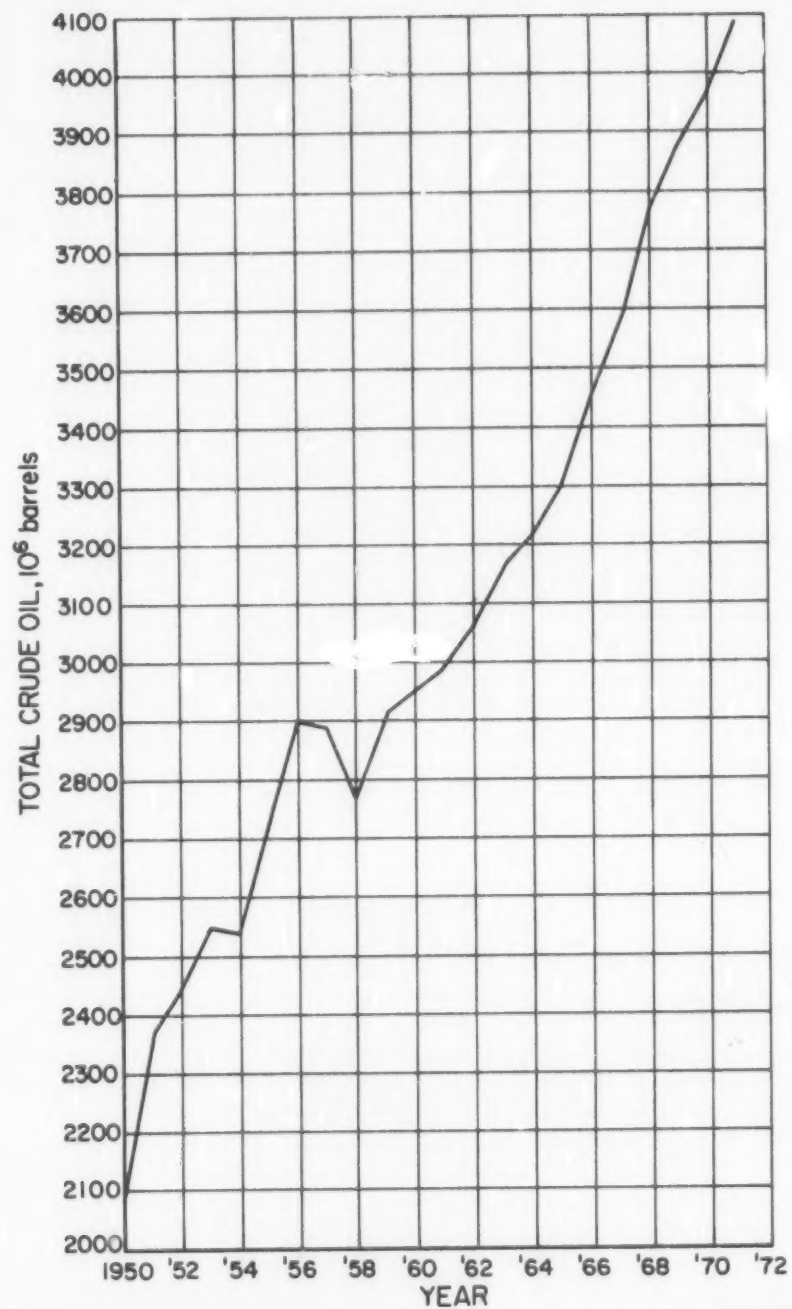
The petroleum-refining industry is the third-largest energy consumer, next to industrial chemicals and iron and steel manufacturing. An estimated 2861 trillion Btu of energy was consumed for petroleum refining in 1971. The 1972 Census of Manufactures¹⁰ indicates that energy consumed for heat and power totaled 1441 trillion Btu in 1971. This figure does not include the large amount of fuels, such as hydrogen, produced and consumed within a refinery, nor does it include energy used for feedstock. In 1971, an estimated 4085 million barrels of crude oil was run to the stills.¹ If the industry continues to grow at its current rate, total annual energy consumption will increase to about 3700 trillion Btu by 1985, and the amount of crude oil run to stills will increase to about 5500 million bbl/yr. (See Figures 1-3.)

There are many sources of air pollutant emissions in a refinery, producing large amounts and a wide variety of emissions. Because of the complexity of a refinery, categorization of emissions by process is very difficult. Many sources, such as gas relief valves, are found in several processes, whereas other sources, such as waste gas flares, cannot be associated with any single process. Thus, the level of each emission must be determined by summation. Air pollutant emissions include particulates, SO_x , carbon monoxide, hydrocarbons, NO_x , aldehydes, and ammonia. The greatest contributors to air pollution are SO_x , carbon monoxide, hydrocarbons, and NO_x .



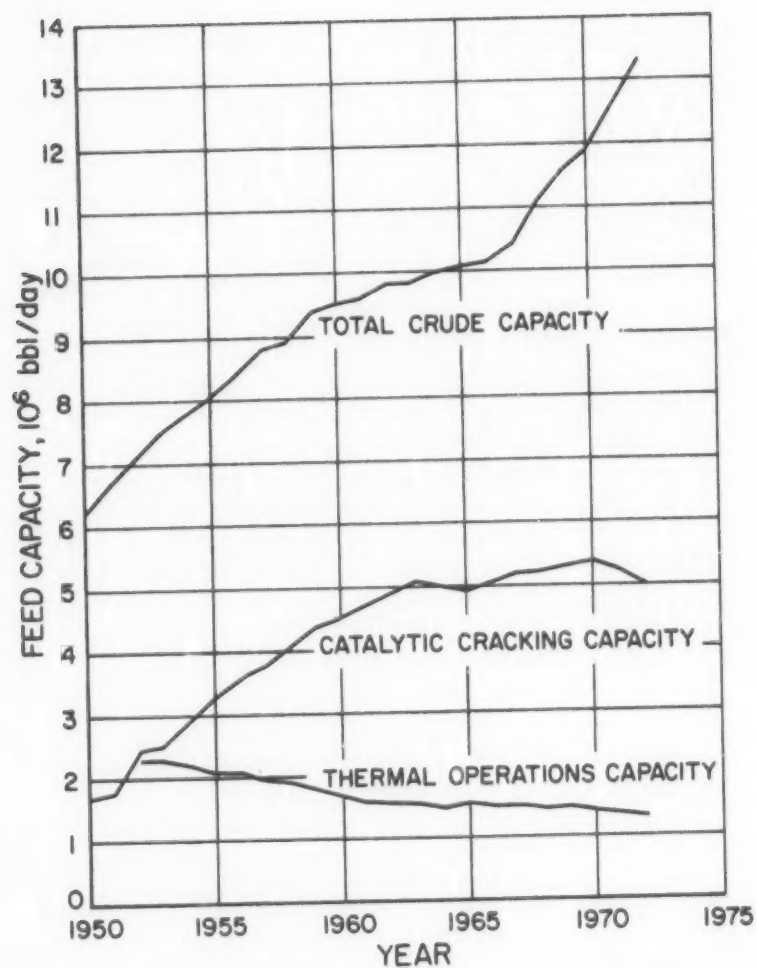
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Figure 1. TOTAL ANNUAL ENERGY CONSUMPTION BY THE PETROLEUM-REFINING INDUSTRY, 1950-1971



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Figure 2. TOTAL CRUDE OIL RUN TO STILLs, 1950-1971



A-54-748

Figure 3. OPERATING CAPACITIES OF OIL REFINERY PROCESSES, 1950-1971

Petroleum Refinery Processes^{3,4,8}

As of January 1, 1973, there were 247 petroleum refineries operating in the U.S.,² each one different from the other, using different processes to produce the final products. Thus, no typical refineries can be used as models for an energy survey. Even though distillation, catalytic cracking, catalytic reforming, and thermal cracking are processes common to all refineries, these processes differ from one refinery to the next in terms of implementation. For example, catalytic cracking can be accomplished by one of several processes, including fluidized-bed cracking, moving-bed cracking, and fixed-bed cracking. Each of these processes, in turn, is varied from refinery to refinery. For this survey, only the major types of processes are discussed.

Separation Processes - Distillation

The refining, or manufacturing, of petroleum products is accomplished by two means: physical means or separation operations, and chemical or conversion processes. The first step in the refining of crude oil is distillation, in which the lighter, more volatile components are separated from the heavier, less volatile components. Several types of equipment can be used in the process; the basic types are shown in Figure 4. Typically, distillation occurs when heated crude oil is admitted into a fractionating column, which is tapped at several points, thus allowing continuous removal of the various boiling fractions, or products. The residue from this process may be submitted to vacuum distillation. When the fractions within the crude have small volatility differences or when it is desired to separate a higher boiling constituent from other components of a system of vapors and gases, additional distillations employing solvents or absorbers are used. Upon completion of distillation operations, the products usually are prepared and fed into the conversion processes.

The energy consumption of a crude oil distillation process varies, depending upon the particular installation, but a review of several processes indicates that a typical installation consumes about 100,000 Btu of fuel per barrel of crude oil feed for heat.⁷ An additional 20,000 Btu of energy is consumed as steam.

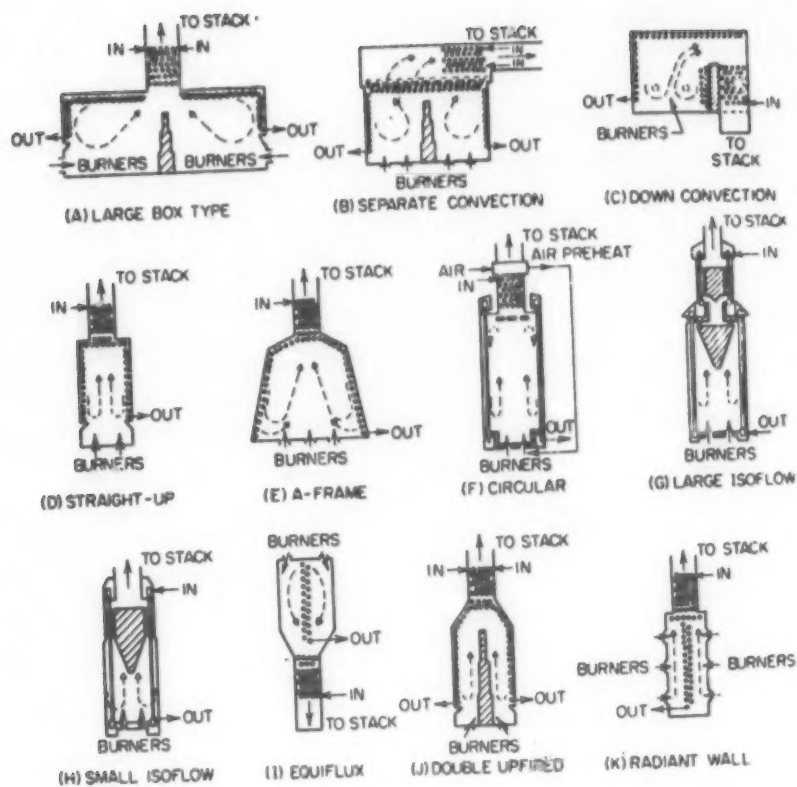


Figure 4. BASIC TYPES OF PIPESTILL HEATERS³

Conversion Processes - Catalytic Cracking

Catalytic cracking is one of the most important processes used in refineries. The estimated feed capacity of catalytic cracking units was 5.5 million bbl/day in 1972² (80% fresh feed, 20% recycle). This represents almost 52% of the total crude oil running capacity in the U.S. (See Figure 3.) The primary purpose of catalytic cracking is to produce gasoline. Chemically, this is accomplished by breaking and rearranging the chemical bonds in large hydrocarbon molecules. In addition to catalysis, cracking also can be accomplished by heating the feed (thermal cracking), but this method is no longer preferred (Figure 3).

As previously stated, the three basic types of catalytic cracking processes are fluidized bed, moving bed, and fixed bed. At present, fluidized-bed cracking accounts for about 80% of the refinery catalytic cracking capacity, and moving-bed cracking accounts for the remaining 20%. The fixed-bed catalytic cracking process is virtually extinct.

In the fluidized-bed process, the reacting vapors (feed) are forced upward through a bed of fine granular material with finely divided solid catalyst evenly distributed throughout the system. By so doing, a quasi-fluid suspension is established, in which the reacting vapors come in contact with the evenly distributed catalyst and undergo cracking. Upon completion of the cracking, the catalyst is separated from the products by cyclone separators. The catalyst, fouled by coke and tar during cracking, must be regenerated. This is done in a separate space by passing air through the bed and burning off these products. Figure 5 is a schematic diagram of one type of catalytic cracking unit in operation.⁸

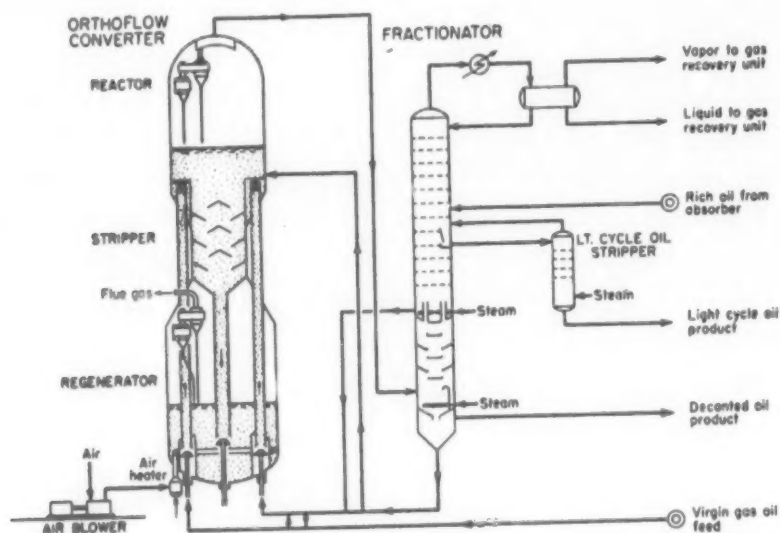


Figure 5. SCHEMATIC DIAGRAM OF ORTHOFLOW CATALYTIC CONVERTER AND ADJUNCTS⁸ (Stippled Areas Represent Fresh or Regenerated Catalyst) (M.W. Kellogg Co.)

The reaction temperatures used in such a unit range from 885° to 950°F, depending upon the yield of products desired. Regenerator temperatures are moderate, ranging from about 1050° to 1200°F. Although operating pressures in this unit are low, 8-20 psi, some cracking processes utilize pressures as high as 1000 psi. During catalyst regeneration, when coke and tar are burned off from the catalyst, the combustion gases (primarily carbon monoxide) are sent to carbon monoxide boilers and burned to produce high-pressure steam. The moving-bed cracking process

is similar, employing instead of a fine-grain catalyst, a flowing bead-type catalyst. (See Figure 5.) Both processes are continuous.

Energy consumption in a typical catalytic cracking process is about 150,000 Btu of fuel and electricity per barrel of feed.^{7*} On the other hand, there is a net steam production of about 75 pounds, which converts to a fuel value of 100,000 Btu/bbl of fresh feed.

Catalytic Reforming

Catalytic reforming also is an important conversion process within a refinery. In this process, certain ring hydrocarbons are converted into aromatic compounds. As of January 1, 1973, the charge capacity for catalytic reforming was almost 3.3 million bbl/day.² As in the case of catalytic cracking, several types of processes are used. In a typical operation, the feed, usually naphtha, is prepared in a prefractionator, mixed with hydrogen, and fed into a preheater, where the temperature of the mixture is increased. The hot naphtha vapors are fed into a reactor containing any of a number of catalysts, depending on the process used. In the reactor, several chemical reactions take place. The products of the reaction are cooled in heat exchangers and then fractionated or stabilized. The stabilized product then can be used for high-octane gasoline, or it can be further fractionated into components (principally benzene, toluene, and xylenes).

Operating conditions of a catalytic reformer vary considerably. Reactor temperatures range from about 800° to 1100°F and pressures range from as low as 100 psi to more than 1000 psi. Energy consumption also varies considerably. Fuel in the form of oil or gas and electricity are the primary types of energy consumed in catalytic reforming. Fuel consumption varies from 200,000 to 450,000 Btu/bbl of feed.⁷ Electric consumption, primarily for driving pumps and compressors, varies from 3000 to 20,000 Btu/bbl of feed.

*

Estimated average based on energy consumed by various processes.

Hydrotreating

Hydrotreating is used in a refinery for removing impurities, including sulfur, nitrogen, and metallic compounds; for hydrogen saturation of olefins and aromatics; and for mild hydrocracking. Hydrotreating is used to prepare catalytic cracker and reformer feedstocks and to upgrade middle distillates, cracked fractions, lubricant oils, gasolines, and waxes. In 1972, refineries had a catalytic hydrotreating charge capacity of nearly 4.4 million bbl/day.

In a typical hydrotreating process, feedstock, made up primarily of petroleum distillates, is mixed with recycle and makeup hydrogen and heated to temperatures of 400⁰-850⁰F. The heated charge then is fed into a fixed-bed reactor containing a catalyst, usually cobalt molybdate on an alumina carrier, and pressurized from 50 to 1500 psig. The effluent is cooled, separated from recycle gas, and stripped of hydrogen sulfide.

As in the other processes discussed, energy consumption varies considerably, depending upon the products desired and the specific process used. Fuel consumption, primarily for heating, varies from 25,000 to about 120,000 Btu/bbl of feed; the majority of processes consume approximately 50,000 Btu/bbl. Electricity consumption is minimal, usually about 7000 Btu/bbl of feed. In addition, about 200 SCF of hydrogen is consumed per barrel of feed. This hydrogen, which should be considered as feedstock, has a heating value of about 65,000 Btu. All the hydrogen used in this process is obtained as off-gas from catalytic reforming processes. The fuels used for heating are primarily natural gas and fuel oil.

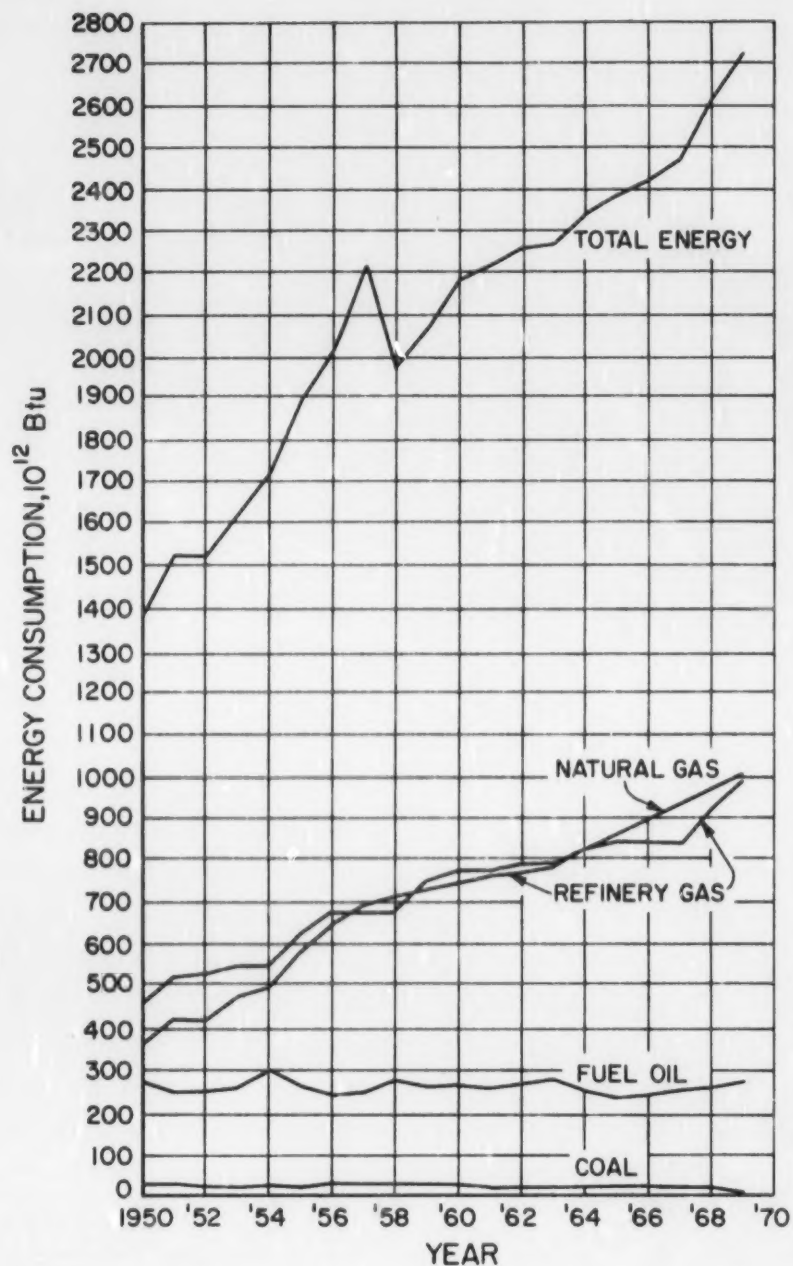
Thermal Processes - Cracking

Thermal processes are processes that decompose, rearrange, or combine hydrocarbons by the application of heat without using catalysts. As shown in Figure 3, the use of thermal processes in refining has been gradually falling off in favor of catalytic processes. The charge capacity for all thermal operations at the end of 1972 was 1.44 million bbl/day, only about 10% of the total crude capacity of refineries.⁷

Numerous processes for thermal cracking are in existence, but very few are used any more. Initially, thermal cracking was used to convert heavy charge oil into gasoline materials, but today conversion by this method is not economical. Instead, existing units are being used to crack heavy catalytic cycle stock that usually goes to fuel oil. In a typical cracking process, the crude oil is separated into various fractions directly in a combination distillation-cracking unit, and the resulting fractions are cracked in continuous operations. Cracking temperatures range from about 900° to 1100°F; operating pressures vary from 600 to more than 1000 psi. Energy consumed in thermal cracking is about 260,000 Btu/bbl of charge⁷; this energy is used for direct heat. Although steam, at pressures up to 300 psig, also is required, there is an overall net production of steam equivalent to about 100,000 Btu/bbl of feed.

Energy Consumption in Petroleum Refining

Approximately 250 refineries are in operation in the U.S. at present, no two of which are alike. Each refinery produces hundreds of products by using the processes that are most suited to the needs of that refinery. The list of factors that affect the choice of process used by a refinery is long, but the primary ones are crude oil source, power source, water availability, and potential markets. As a result, the energy consumed by a refinery to process a barrel of crude oil varies considerably. A reasonable average, determined by taking the total energy consumption of the industry and dividing by the number of barrels of crude oil run to stills, is about 700,000 Btu/bbl of crude oil processed. Figure 6 compares the various forms of energy consumed by refineries and shows that about two-thirds of the total energy consumption is in the form of natural gas and refinery gas. Purchased electricity, not shown in Figure 6, accounts for less than 3% of the total energy consumption. Other forms of energy, which make up the balance of energy consumed but are not shown in Figure 6, are acid sludge, petroleum coke, liquified petroleum gas, and purchased steam.¹ Together these forms of energy account for about 16% of the total energy consumed by this industry.



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Figure 6. TYPES OF FUEL CONSUMED
BY PETROLEUM REFINERIES¹

Over the years, the amount of energy consumed per barrel of crude oil run to the stills has remained fairly constant. Since 1950, the energy consumed per barrel of crude oil run has ranged from a low of 626,000 Btu to a high of 770,000 Btu. (See Figure 7.)

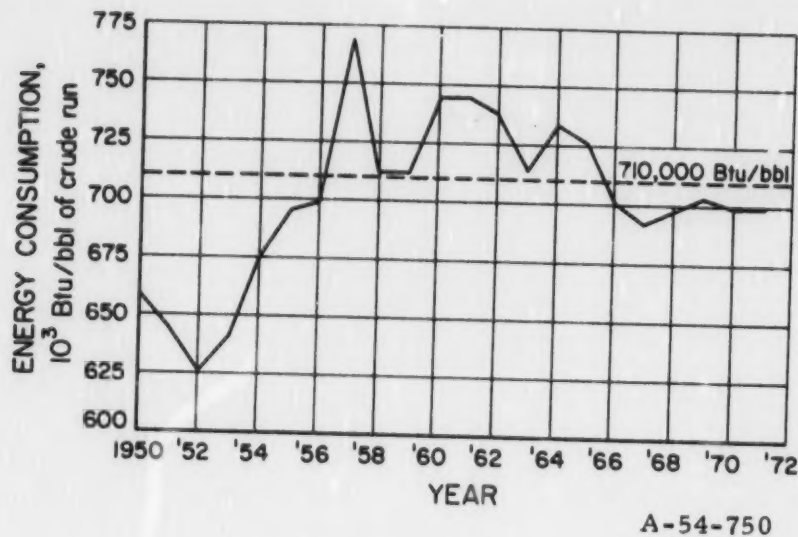
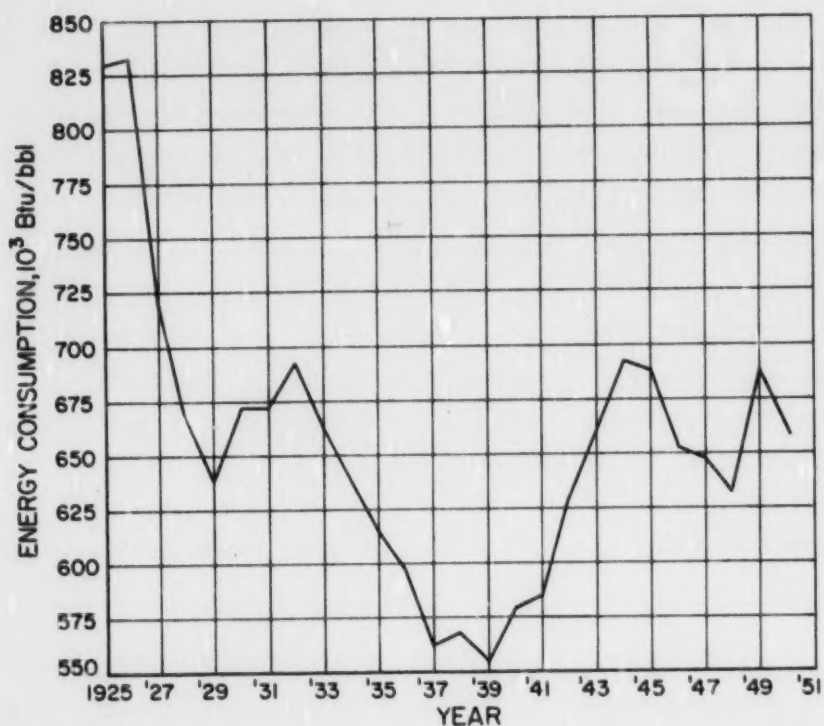


Figure 7. AVERAGE ENERGY CONSUMED PER BARREL OF CRUDE OIL RUN TO STILL¹

Although this is a wide range, most of the time this figure was within 5% of 710,000 Btu/bbl of crude oil over the 22 years covered by these data. During the last 3 or 4 years, this figure has hovered around 700,000 Btu/bbl of crude oil run. Prior to 1950, this figure was consistently below 700,000 Btu/bbl. (See Figure 8.) These data indicate that the energy consumed per unit of crude oil can be reduced significantly over current values. However, information on the method of data collection is not available; thus, it is conceivable that these data are the result of changes in collection methodology from year to year and cannot be compared. What is more likely is that the product mix has changed over the years, which, in turn, would affect energy consumption by forcing refineries to alter their processes accordingly.



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Figure 8. ENERGY CONSUMPTION PER BARREL OF CRUDE OIL RUN, 1925-1950¹

Short of drastic changes in the product mix, the energy consumption of petroleum refineries per barrel of crude oil run is not likely to decrease very much in the future. Because fuel is a major cost item for refineries, they do attempt to cut their needs to a minimum, a minimum that the data suggest is currently around 700,000 Btu/bbl of crude oil run to stills based on the current product mix. Fuel used by this industry is primarily for direct heating of feedstocks (60%), process steam production (34%), and electric generation (6%).⁹ Over the years, the percentage of energy consumed as direct heat has not changed very much, increasing by only 1% since 1960. With this energy usage pattern, it is difficult to foresee much of a change in the future.

Of course, new processes are constantly being developed to improve refinery operations, but they do not seem to have much effect on the energy consumption pattern. For example, several different catalytic cracking processes are in use, yet the energy consumed by these processes varies over a relatively narrow range. In addition, if all the refineries were to adopt the process that consumes the least amount of energy, that process might be incompatible with other phases of the operation, which might then increase energy consumption.

In short, the energy utilization of a petroleum refinery is very closely tied to the interrelationships of the processes used. Substituting one process for another because it consumes less energy could alter the energy consumption characteristics of the rest of the refinery, resulting, perhaps, in a net increase in energy consumption for that refinery. Given these considerations and the complexity of the industry, the industry as a whole probably will not reduce its energy consumption per barrel of crude oil run to stills without altering the product mix.

Air Pollutant Emissions From Petroleum Refineries

The major air pollutant emissions from petroleum refineries are SO_x , carbon monoxide, NO_x , hydrocarbons, aldehydes, ammonia, and particulates. These emissions cannot be categorized by process because some emission sources are found throughout a refinery, whereas others are not associated with any one process. The refinery must be treated as an integrated system of pumps, valves, cooling towers, process heaters, and other equipment. Table 1 summarizes the potential sources for each type of emission from petroleum refineries.⁶

Table 1. POTENTIAL SOURCES OF SPECIFIC EMISSIONS FROM OIL REFINERIES⁶

Emission	Potential sources
Oxides of sulfur	Boilers, process heaters, catalytic cracking unit regenerators, treating units, H ₂ S flares, desolting operations.
Hydrocarbons	Loading facilities, turnarounds, sampling, storage tanks, waste water separators, blow-down systems, catalyst regenerators, pumps, valves, blind changing, cooling towers, vacuum jets, barometric condensers, air-blowing, high pressure equipment handling volatile hydrocarbons, process heaters, boilers, compressor engines.
Oxides of nitrogen	Process heaters, boilers, compressor engines, catalyst regenerators, flares.
Particulate matter	Catalyst regenerators, boilers, process heaters, desolting operations, incinerators.
Aldehydes	Catalyst regenerators.
Ammonia	Catalyst regenerators.
Odors	Treating units (air-blowing, steam-blowing), drains, tank vents, barometric condenser sumps, waste water separators.
Carbon monoxide	Catalyst regeneration, desolting, compressor engines, incinerators.

In addition, because petroleum refineries differ so widely, emissions can only be estimated, rather than quantified throughout the industry. Usually these estimates can be based on the amount of fuel burned or the amount of feed processed.

Hydrocarbons

Hydrocarbon emissions from a petroleum refinery vary according to the throughput of crude oil. The values range from about 0.1 to 0.6% by weight of the crude throughput; the lower value is representative of refineries with extensive pollution control equipment. Smaller refineries with distillation, treating, and blending processes only tend to be at the lower end of this range, whereas complex refineries cover the full range. Tables 2, 3, and 4 summarize the factors for hydrocarbon emissions from combustion sources, equipment leakage, and miscellaneous processes such as vacuum jets and cooling towers, respectively.

Storage tanks and loading operations are the largest sources of hydrocarbon emissions, accounting for nearly one-half of the total hydrocarbon emissions from refineries. Hydrocarbon emissions vary from 100 to 1000 lb/1000 bbl of refinery capacity. The actual number depends upon the type of equipment and controls used and, consequently, does not lend itself to detailed analysis.

In general, combustion operations are not a major source of hydrocarbon emissions. Table 2 shows that, of the major combustion operations, fluid catalytic cracking units are the most offensive. Assuming that 80% of all catalytic cracking capacity is of the fluidized-bed type, about 180,000 tons of hydrocarbons could have been emitted by these units in 1972. An additional 18,000 tons could have been emitted by moving-bed catalytic units.

Table 2. FACTORS FOR HYDROCARBON EMISSIONS FROM COMBUSTION SOURCES⁶

Source	Units of factor	Value
Boilers and process heaters.....	Pounds per 1,000 cubic feet of fuel gas burned.	0.005
	Pounds per barrel of fuel oil burned.....	.14
Fluid catalytic cracking units.....	Pounds per 1,000 barrels fresh feed.....	300
Moving-bed catalytic cracking units.....	Pounds per 1,000 barrels fresh feed.....	87
Compressor internal combustion engines.....	Pounds per 1,000 cubic feet of fuel gas burned.	1.3

Hydrocarbon emissions also occur as the result of the combustion of fuel gas (both natural gas and refinery gas) and fuel oil in process heaters, boilers, and internal combustion engines for driving compressors. No accurate figures on the consumption of refinery gas and fuel oil in 1971 are available, but based on the consumption of these fuels by the industry in the recent past, reasonable estimates of hydrocarbon emissions can be made. In 1971, approximately 1.3 trillion CF of natural gas was consumed by this industry. In recent years, refinery gas consumption has been nearly equal to natural gas consumption. (See Figure 6.) Thus, a total fuel gas consumption of about 2.6 trillion CF in 1971 is not an unreasonable assumption. Based on this assumption and assuming 95% of this amount was consumed in process heaters and boilers and only 5% in internal combustion engines, total hydrocarbon emissions as a result of the combustion of fuel gas would have been approximately 110,000 tons in 1971. Hydrocarbon emissions as a result of the combustion of fuel oil in boilers and process heaters are estimated at about 5220 tons in 1971. This is based on an estimated fuel oil consumption of 46 million barrels in 1971. Thus, the total amount of hydrocarbon emissions from combustion sources in 1971 is estimated to have been about 310,000 tons.

As shown in Tables 3 and 4, there are sources of hydrocarbon emissions other than combustion sources. However, detailed information on these other sources is seldom available. Thus, in Table 3, two factors are presented for each source: One is based on the emissions from a specific piece of equipment and the other is an overall average for a refinery based on feed capacity. Because these emissions result from leaks, the degree and effectiveness of maintenance in the refinery will have a pronounced effect on emission rates. The factors given in Table 3 are average emission rates, but they assume a high degree of maintenance. It also has been assumed that maintenance is the only control activity used, although blowdown systems may be used by some refineries, in which case emissions would be reduced. Based on the factors presented in Table 3 and given a total U.S. refinery capacity of 13.4 million bbl of crude oil per day, approximately 150,000 tons of hydrocarbons were emitted from these sources in 1972.

Table 3. FACTORS FOR HYDROCARBON EMISSIONS FROM EQUIPMENT LEAKAGE⁶

Source	Units of factor	Value
Pipeline valves.....	Pounds per day per valve.....	6.18
Vessel relief valves.....	Pounds per day per valve.....	2.4
Pipeline relief valves.....	Neg.	
Pump seals.....	Pounds per day per seal.....	4.9
Compressor seals.....	Pounds per day per seal.....	8.8
Pipeline valves.....	Pounds per 1,000 barrels refinery capacity.....	38
Vessel relief valves.....	Pounds per 1,000 barrels refinery capacity.....	11
Pump seals.....	Pounds per 1,000 barrels refinery capacity.....	17
Compressor seals.....	Pounds per 1,000 barrels refinery capacity.....	8

Table 4 shows hydrocarbon emissions from miscellaneous process equipment, which can be major sources of emissions. When a range of values is given, the low numbers are indicative of a plant using control techniques and the high numbers are estimated emissions from a plant without extensive controls. The sources shown as "other" in Table 4 include air-blowing, pipeline blind changing, and sampling. Because of the high degree of uncertainty involved, attempts to summarize these numbers should not be made.

Table 4. FACTORS FOR HYDROCARBON EMISSIONS FROM MISCELLANEOUS PROCESS EQUIPMENT⁶

Source	Units of factor	Value	Range of values
Blowdown systems.....	Pounds per 1,000 barrels refining capacity.....		5-300
Process drains and waste water separators.....	Pounds per 1,000 barrels waste water processed.....		8-210
Vacuum jets.....	Pounds per 1,000 barrels vacuum distillation capacity.....		0-110
Cooling towers.....	Pounds per million gallons cooling water circulated.....	6	
Other.....	Pounds per 1,000 barrels refinery capacity.....	10	



SO_x emissions are a direct function of the sulfur content of the crude oil being processed, and as such, they vary considerably and do not lend themselves to estimation. The sulfur that goes into the refinery in crude oil, in purchased fuel oil or gas, and as sulfuric acid leaves the refinery in the various products, as spent sulfuric acid, as sulfides and sulfates, and in the liquid wastes; or it is recovered in sulfur-recovery plants.

The difference between what goes in and what comes out is emitted to the atmosphere as sulfur dioxide, sulfur trioxide, and hydrogen sulfide.

Miscellaneous Emissions

Other emissions from petroleum refineries are carbon monoxide, NO_x , aldehydes, organic acids, ammonia, and particulate matter. These emissions are discharged from combustion sources, which include catalyst regeneration units, boilers and process heaters, and internal combustion engines. Tables 5 and 6 summarize these emission factors.

Table 5. FACTORS FOR PARTICULATE EMISSIONS⁶

Source	Units of factor	Value
Boilers and process heaters	Pounds per 1,000 cu. ft. of fuel gas burned	0.02
	Pounds per barrel of fuel oil burned	.8
Fluid catalytic units:		
With electric precipitation	Percent of catalyst circulated	.0000
Without electric precipitation	Percent of catalyst circulated	.005
Moving-bed catalyst units, high efficiency centrifugal separators	Percent of catalyst circulated	.005

Table 6. FACTORS FOR EMISSIONS OF NO_x , CARBON MONOXIDES, ALDEHYDES, AND AMMONIA FROM OIL REFINERIES⁶

Source	Units of factor	Value of factor for various emissions			
		NO_x as NO_2	CO	Aldehydes as HCHO	Ammonia as NH_3
Boilers and process heaters	Pounds per 1,000 cu. ft. of fuel gas burned	0.25	Neg.	0.0001	Neg.
	Pounds per barrel of fuel oil burned	2.9	Neg.	.005	Neg.
Compressor internal combustion engines	Pounds per 1,000 cu. ft. of fuel gas burned	.86	Neg.	11	0.2
Fluid-bed catalytic cracking units	Pounds per 1,000 barrels of fresh feed	88	12,700	19	54
Moving-bed catalytic cracking units	Pounds per 1,000 barrels of fresh feed	5.0	3,800	12	5.0

Table 7 summarizes these emissions on an annual basis using 1971 production data. The data presented in Table 7 were calculated by assuming 365 days of operation, fuel gas consumption of 2.6 trillion CF/yr, and fuel oil consumption of 46 million bbl/yr. In addition, it was assumed that 80% of the catalytic cracking capacity was of the fluidized-bed type.

Table 7. ANNUAL EMISSION RATES FOR NO_x, CARBON MONOXIDE, ALDEHYDES, AMMONIA, AND PARTICULATES

Source	Air Pollutant			
	NO _x (as NO ₂)	Aldehydes (as HCHO)	Ammonia (as NH ₃)	Particulates
		tons/year		
Boilers and Process Heaters	350,750	Negl	Negl	43,100
Fluid Catalytic Cracking Units	41,610	9,026,000	35,600	--†
Moving-Bed Catalytic Cracking Units	823	626,000	823	--†
Compressor Internal Combustion Engines	55,900	Negl	13,000	--
Total	449,083	9,652,000	49,423	43,100

* Rates calculated from data presented in Reference 6.

† Cannot be determined.

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The figures for air pollutant emissions presented here are estimates only and should not be assumed accurate for every refinery. The only way to determine the emissions from a given facility is to measure them.

Trends in Air Pollutant Emissions

As in the case of fuel consumption, it is difficult to assess the effect of future production methods on air pollutant emissions. Numerous methods can be used for controlling emissions from the various sources, as shown in Table 8. Because air pollution controls are not 100% efficient, emissions continue to occur. Consequently, total annual emissions will increase as the feed input increases. However, this increase could be minimized if new control equipment, with better efficiencies than those already in use, were developed and installed.

Table 8. SUGGESTED CONTROL MEASURES FOR REDUCING AIR CONTAMINANTS FROM PETROLEUM REFINING⁵

Source	Control method
Storage vessels	Vapor recovery systems; floating-roof tanks; pressure tanks; vapor balance; painting tanks white
Catalyst regenerators	Cyclones - precipitator - CO boiler; cyclones - water scrubber; multiple cyclones
Accumulator vents	Vapor recovery; vapor incineration
Blowdown systems	Smokeless flares - gas recovery
Pumps and compressors	Mechanical seals; vapor recovery; sealing glands by oil pressure; maintenance
Vacuum jets	Vapor incineration
Equipment valves	Inspection and maintenance
Pressure relief valves	Vapor recovery; vapor incineration; rupture discs; inspection and maintenance
Effluent-waste disposal	Enclosing separators; covering sewer boxes and using liquid seal; liquid seals on drains
Bulk-loading facilities	Vapor collection with recovery or incineration; submerged or bottom loading
Acid treating	Continuous-type agitators with mechanical mixing; replace with catalytic hydrogenation units; incinerate all vented gases; stop sludge burning
Acid sludge storage and shipping	Caustic scrubbing; incineration; vapor return system; disposal at sea
Spent-caustic handling	Incineration; scrubbing
Doctor treating	Steam strip spent doctor solution to hydrocarbon recovery before air regeneration; replace treating unit with other, less objectionable units (Mercox)
Sour-water treating	Use sour-water oxidizers and gas incineration; conversion to ammonium sulfate
Mercaptan disposal	Conversion to disulfides; adding to catalytic cracking charge stock; incineration; using material in organic synthesis
Asphalt blowing	Incineration; water scrubbing (nonrecirculating type)
Shutdowns, turnarounds	Depressure and purge to vapor recovery

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VI. SIC CODES 3211, 3221, AND 3229 - FLAT GLASS, CONTAINER GLASS, AND PRESSED AND BLOWN GLASS AND GLASSWARE

Summary

The glass industry in the United States consumes about 1.5% of the total energy consumed by industry annually. The energy consumed by the glass industry in 1971 was estimated at about 250 trillion Btu.⁶ The primary forms of energy consumed are natural gas, fuel oil, and electricity; the percentage of coal consumed is very small. During the 1960's, the glass industry grew at the rate of 4.5% per year, and this trend is expected to continue through 1980. At this rate, energy consumption will increase to about 375 trillion Btu/yr, a growth of 50%.

The potential for reducing the projected amount of energy required to produce a ton of glass is not good. The use of oxygen in the melting furnace can decrease energy consumption by about 10% in a fuel-fired melter. The use of agglomerated batch can increase the melting rate of the raw materials, thus reducing the energy required to melt a ton of glass. Precise control of combustion in the melter through proper burner positioning and automatic furnace controls also can improve fuel efficiency.

However, these new technologies will require considerable development before they become commercially acceptable. Each of these processes presents technical problems that must be overcome. Our best estimate is that these processes for reducing fuel consumption will not have a significant impact on the glass industry for at least 8-10 years. Historically, the glass industry has been slow to both develop and implement new technology because of the high starting cost compared to the marginal profit of producing glass.

Moreover, as the availability of fossil fuels decreases and air pollution regulations become tighter, the industry is expected to turn toward more electric melting. Nevertheless, electric melting ultimately consumes more energy per ton of glass produced than the direct use of fossil fuels if the energy consumed for generating the electricity is included. New technology utilizing a fuel-fired submerged combustion melter also is being developed and has the potential for reducing fuel consumption per ton of glass melted by

as much as 40% while also reducing pollutants. At the same time, the use of agglomerated batch, which can decrease energy consumption, also reduces air pollutant emissions. However, again, submerged combustion and agglomerated batch are expected to have a small impact in the next 10 years compared to the growth of electric melting for pollution control.

Glass-Manufacturing Processes

The glass industry is broken down by four-digit SIC codes into three categories: glass containers (SIC Code 3221), flat glass (SIC Code 3211), and pressed and blown glass and glassware (SIC Code 3229).

The glass container industry is engaged primarily in the production of glass containers for commercial packing and bottling for home consumption. In 1971, an estimated 10.9 million tons of glass were melted in the container industry. This estimate is based on the number of containers produced, as reported by the Bureau of the Census, assuming an average weight of 8 oz/container.⁹ In addition, an estimated 15% of the glass produced is recycled back to the melting process as cullet and subsequently remelted; this also is included in the estimate of total production for 1971. Total energy consumption by the container industry in 1971 was 130.4 trillion Btu.

The flat glass industry is engaged primarily in the production of flat glass products, such as plate glass, sheet (window) glass, float glass, rolled glass, and figured and wired glass. Also included within this classification are companies producing laminated glass from glass made by other companies. In 1972, an estimated 2.56 million tons of flat glass was melted; 45% was classified as sheet glass, and the remaining 55% was primarily plate glass, float glass, and rolled glass.⁸ These figures include a 25% recycling of cullet back to the melting process. This estimate is based on the production statistics reported by the Bureau of the Census. In addition, the average glass density is estimated at 0.82 tons/1000 square feet, and in the case of sheet glass there are 50 square feet of glass to a box. The total amount of energy consumed by the flat glass industry in 1971 was 55.9 trillion Btu.

The pressed and blown glass and glassware industry primarily produces glass and glassware (not elsewhere classified) pressed, blown, or shaped from glass produced from the same establishment. This classification includes companies that deal in textile-type glass fiber products but not glass wool insulation products. Also included are companies engaged in the manufacturing of pressed lenses for headlights, beacons, and lanterns but not optical lenses. Estimated production during 1971 is 3.5 million tons of glass.⁷ This estimate is based on a 20% recycle of glass for cullet. Energy consumption by this industry in 1971 is estimated at 63.1 trillion Btu.

The manufacturing of glass involves three major energy-consuming processes: melting the raw materials, refining the molten glass, and finishing the formed products (Figure 1). Typically, about 80% of the energy consumed by the glass industry is for melting and refining, 15% is for finishing, and 5% is for mechanical drives and conveyors.

The first step in the manufacturing of glass is the preparation of the raw glass batch. In this process, the various raw materials, such as sand, limestone, soda ash, and various minor ingredients (fluxes and colorizers or decolorizers), are weighed in a batch hopper and dumped into a mixer. Water usually is added at this point and thoroughly mixed. The material is transferred to a storage hopper from which it is charged into the furnace. Energy consumed by this process is electrical and is used to drive the mixers and conveyors.

The second step in the manufacturing of glass is the melting of the raw materials and refining of the molten glass. This process consumes approximately 80% of the total energy consumed by the industry. In 1971, energy consumed for melting was about 200 trillion Btu. Natural gas, fuel oil, or electricity is used in this process, but natural gas is preferred at present. Approximately 75% of the energy consumed by melting furnaces is natural gas.

Melting practices are essentially the same throughout the glass industry, regardless of the end product. Most of the raw materials are converted to glass in continuous reverberatory furnaces equipped with checkerbrick regenerators for preheating the combustion air. These furnaces generally are classified by the firing arrangement used: end-port

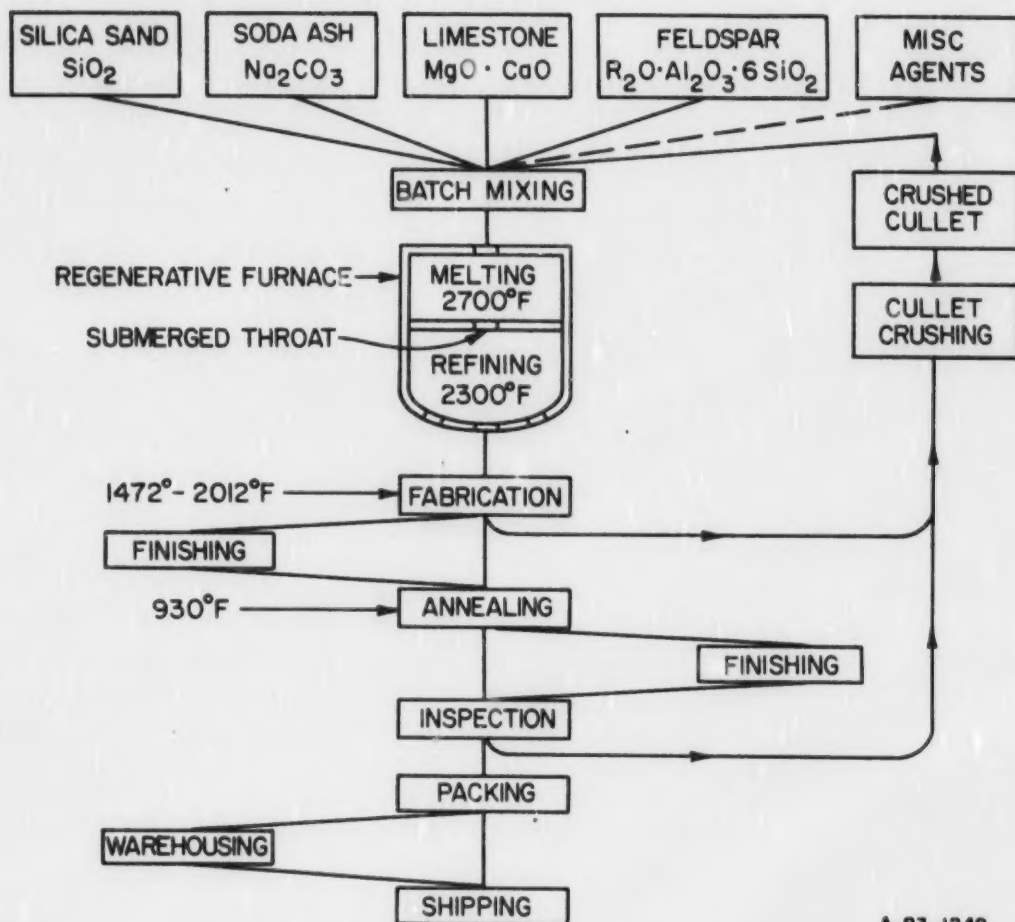


Figure 1. FLOW DIAGRAM FOR SODA-LIME GLASS MANUFACTURE

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or side-port melters. These melters are operated at temperature continuously throughout a campaign that normally lasts 4-5 years. The refiner may or may not be separate from the melter. If it is a part of the melter, the refiner is physically separated from the melting area of the furnace by a shadow wall, but it gets its heat from the melter. Refiners that are separate units are heated independently of the melter.

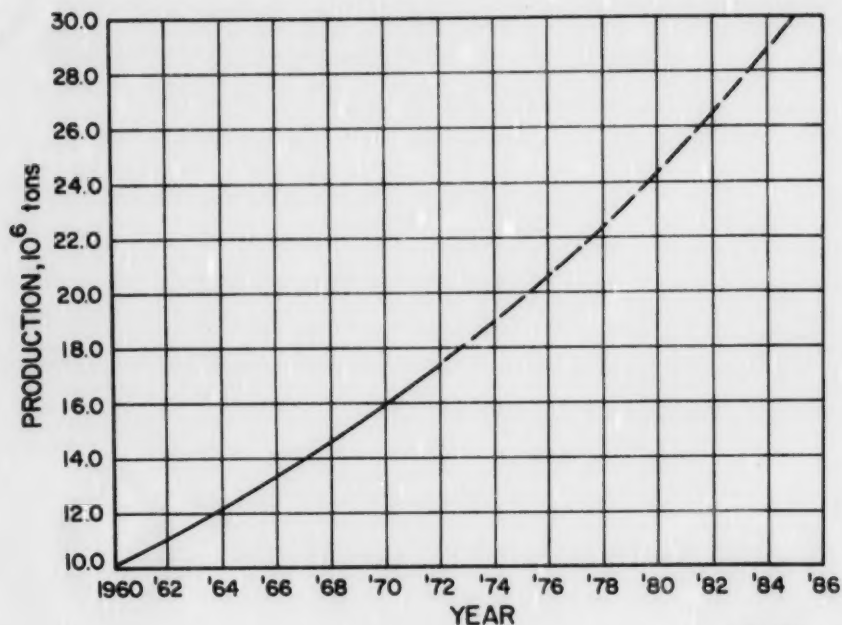
Continuous melters operate by using a reversal system. In this system, fuel and combustion air enter on one side of the furnace, and the combustion products exit on the other side. After about 20 minutes, the melter is reversed; the exit ports become the entrance ports, and the entrance ports become the exit ports. These continuous melters usually are used by the container and flat glass industries. Most of the melters in the pressed and blown glass industry are day tanks, unit melters, and pot melters, many of which are batch-type melters.

The third step in the manufacturing of glass is the processing and finishing of the glass. After the glass has been melted and refined, it is pulled from the furnace. In the container industry, the glass normally is fed into forming machines that blow it into the desired container. In the flat glass industry, the glass is drawn, rolled, or floated to form sheets. In the pressed and blown glass industry, much of the glassware is made by hand.

After the glassware has been formed, it is annealed in lehrs. This process prevents strains from developing in the glass during cooling. In the annealing process, the pressed and blown glassware and the containers are placed on a continuous, mesh-belt conveyor and passed through a tunnel-type oven zoned such that the cooling curve of the ware precisely matches that required to produce a strain-free product. Sheet and plate glass are annealed in a similar manner, except for the conveying mechanism.

Energy Utilization Pattern

Figures 2 and 3 show the annual production and energy consumption of the entire glass industry from 1960 to 1972. In addition, these figures show a 50% projected increase in production and a 50% projected increase in energy consumption through 1980. However, this growth depends upon several factors. The recent boom in the container industry has been

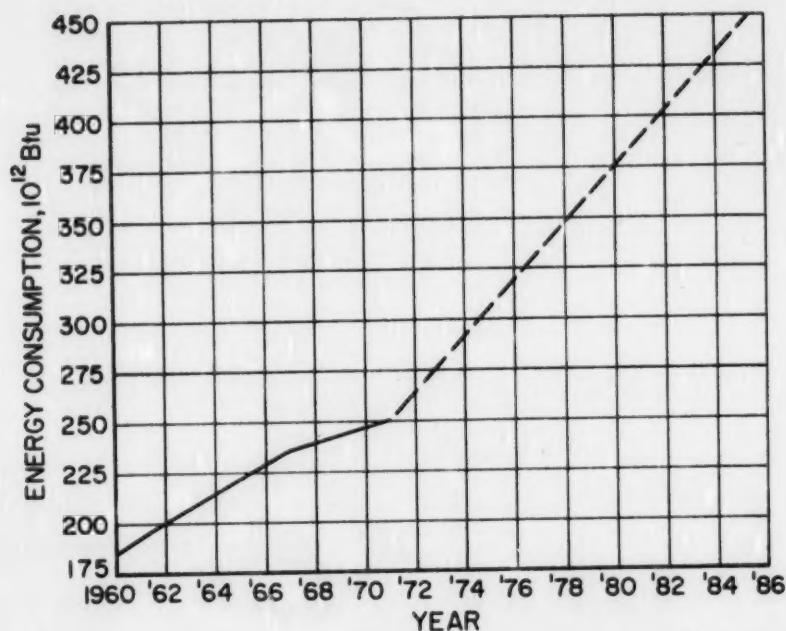


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Figure 2. GROWTH RATE OF GLASS INDUSTRY IN TERMS OF ANNUAL PRODUCTION RATE (Projected After 1972)

due to the popularity of the nonreturnable container, but environmental concerns are causing the industry to revert back to returnable containers.

The growth of the flat glass industry depends upon the growth of the construction industry, because much of the glass produced is used in houses and buildings. In recent years, construction declined for a variety of reasons, and this has led to declines in flat glass production. This trend appears to be reversing itself. In addition, the flat glass industry produces the glass used in automobiles. Automobiles use about 70% of the plate glass manufactured in this country. Thus, any large reductions in automobile production will adversely affect the glass industry.

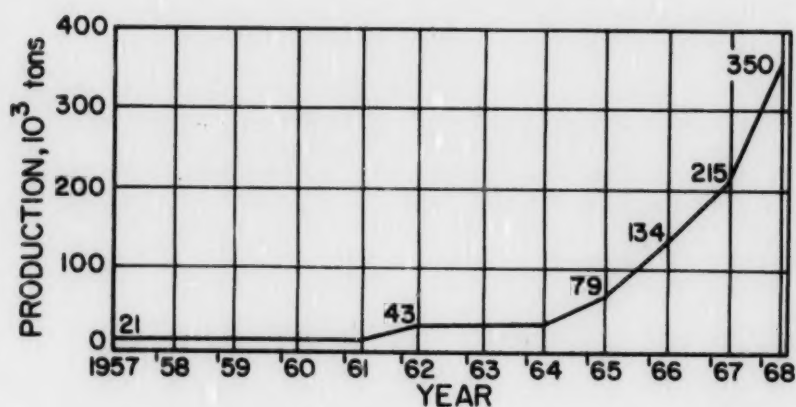


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Figure 3. TOTAL ANNUAL ENERGY CONSUMPTION
BY GLASS INDUSTRY (Projected After 1972)

In the past, the glass industry has met its energy needs with natural gas. Natural gas is preferred because it is a clean-burning fuel that does not affect such glass characteristics as color. In addition, the natural gas flame, when properly controlled, provides for a longer furnace life. Oil flames are very hard on refractories.

At present, electric melting is gaining in usage, but still represents an extremely small amount of the total energy used to melt glass. Figure 4 shows that, from 1961 to 1968, annual glass production by electric melters increased from 21,000 to 350,000 tons. Electric melters are used primarily in the container industry, but other segments of the glass industry are expected to turn to electric melting. Proponents of electric melting equipment claim lower construction costs, better melter efficiencies, better working environments, and less air pollution. These



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Figure 4. ELECTRIC GLASS MELTERS IN USE OR UNDER CONSTRUCTION IN U.S.

advantages are offset by higher energy costs, less turndown flexibility, and greater refractory wear. As air pollution regulations become stricter and as natural gas supplies diminish, the use of electric melting will grow rapidly.

The use of coal is restricted to a few small hand shops in the pressed and blown glass industry. In general, coal is not an acceptable fuel because of its burning characteristics, its sulfur content, and its deleterious effect on glass quality and because, as a fuel, it causes air pollution. Shops that use coal are expected to switch to a cleaner fuel in the near future.

Energy Requirements of the Glass-Melting Process²

Glass melting is the major energy-consuming process in the glass industry. Efficiencies of continuous melters vary considerably, depending upon basic design as well as furnace age, type of glass being melted, and the end use of the product. In the container glass industry, most glass companies claim to operate at a fossil-fuel consumption level of 4.0-7.0 million Btu/ton of glass melted. In the flat glass industry, fossil-fuel consumption is 6.0-12.0 million Btu/ton of glass melted. In the pressed and blown glass industry, fossil-fuel consumption varies from 6.0 to 40.0 million Btu/ton of glass melted, and many companies consume between 30.0 and 40.0 million Btu/ton of glass melted.

Note that these fuel consumption figures apply to furnaces during melting operations. However, data on energy utilization (Table 1) indicate that energy consumption is actually higher because many times during the year operation is suspended for breakdowns and holidays.

Table 1. BREAKDOWN OF ENERGY CONSUMPTION
BY THE GLASS INDUSTRY IN 1971*

	Flat Glass (SIC Code 3211)	Containers (SIC Code 3221)	Pressed and Blown Glass (SIC Code 3229)	Total
Glass Produced, 10 ⁶ tons	2.56	10.90	3.50	16.96
Energy Consumption, 10 ¹² Btu				
Melting	44.7	104.3	50.5	199.5
Annealing	8.4	19.6	9.5	37.5
Other	2.8	6.5	3.2	12.5
Total Energy Consumption, 10 ¹² Btu	55.9	130.4	63.1	249.4
Average Energy Consumption for Melting, 10 ⁶ Btu/ton of glass	17.5	9.6	14.4	11.8
Average Energy Consumption for Entire Production, 10 ⁶ Btu/ton	21.8	12.0	18.0	14.7

* Excludes energy consumed for electricity generation.

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During these periods, the furnaces are idled to maintain furnace temperature while production stops. Thus, energy is consumed but no glass is produced, thereby increasing the overall average energy consumption per ton of glass produced. An even greater source of discrepancy is the variation in the amount of cullet used from one glass plant to the next. The amount of cullet charged varies from 10 to 30% of the total raw material charged to the melter. Lower percentages of cullet charged result in higher fuel consumption. In general, economic considerations prevent higher percentages of cullet from being charged.

These figures indicate that the container glass melters are operated most efficiently. The glass in the flat glass industry is of higher quality than that in the container glass industry; thus, gas bubbles (seeds) and unmelted raw batch (stones) cannot be tolerated. Consequently, furnaces in the flat glass industry* are very large compared with other glass industry furnaces to allow for the long soak periods required to remove all impurities such as entrapped gases and solid batch particles. In the container industry, the furnaces are smaller, and shorter retention times are used because glass quality is not so critical.

* Perhaps 8 sq ft of melting area per ton of glass melted per day in the flat glass industry versus 4 sq ft of melting area per ton of glass melted per day in the container industry.

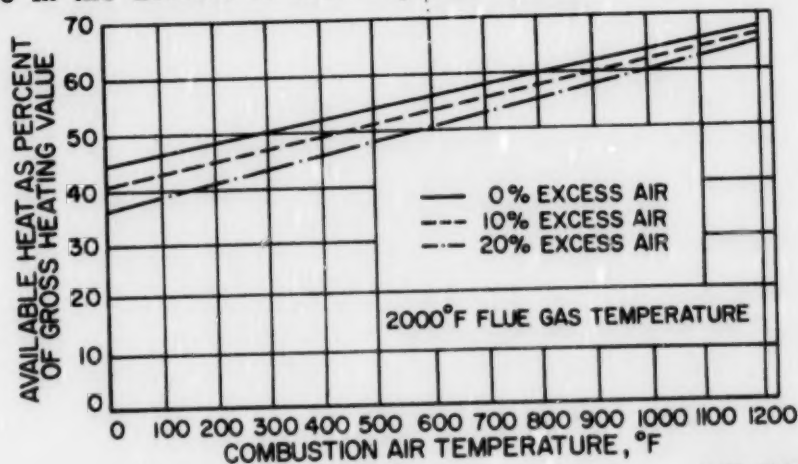
Electric melters require less energy to melt a ton of glass than fuel-fired melters. However, if the energy, which is usually fossil fuel, used to generate the electricity also is considered, total energy consumption per ton of glass is higher than for fuel-fired melters. Typically, an all-electric melter requires about 2.9 million Btu to melt a ton of glass; this is a melting efficiency of about 65%. But the fuel that is consumed to generate this electricity is about 8.7 million Btu, based on a 30% efficiency of generation. Consequently, the "real" amount of energy consumed to melt glass in an all-electric melter is 8.7 million Btu/ton.

In the pressed and glass blown industry, glassware is made by machine and by hand. The furnaces vary from the large continuous type to small pot furnaces. As a result, energy consumption per ton of glass produced varies widely.

As previously stated, the type of glass being melted affects the energy consumption of a furnace. For example, glass color affects furnace efficiency. Most of the heat transferred to the glass from the flame and refractories is by radiation. However, as the color of glass changes, its absorptivity also changes. Consequently, certain colored glasses actually receive less heat from a given flame than others. Glasses that contain a high percentage of silica (70% and above) generally require very high melting temperatures (3000°F). Consequently, energy consumption is quite high. However, very little of this glass is produced because of the expense involved in building and operating a facility at these high temperatures. Soda-lime glass, which melts at considerably lower temperatures (2500°F), is the most commonly melted glass. Theoretical energy requirements are about 2.0 million Btu/ton of glass melted. Other types of glasses that are manufactured in the U.S. are borosilicate, lead silicate, and aluminosilicate. All these glasses require more than 2.0 million Btu/ton to melt. However, the changes in glass composition that normally occur during mixing of the raw materials are not likely to cause changes in energy consumption.

The most significant factors that affect energy consumption of a glass melter are the combustion characteristics and equipment. Thus, mixing characteristics of the air and fuel, the air-to-fuel ratio, the type of burners used, and burner positioning are all important. Historically, U.S. glass furnaces use 20% and higher excess air for combustion, thus

ensuring complete combustion of the fuel. However, the use of excess air is very costly in terms of thermal efficiency and energy consumption. Figure 5 shows the effect of excess air on available heat. The available heat is the gross quantity of heat released minus losses in the flue gases, that is, the quantity of heat that is actually usable in the heating process. As available heat decreases, more fuel must be consumed to supply the necessary heat for melting. Figure 5 also shows that preheating the combustion air increases the available heat and, consequently, results in a decrease in the amount of fuel required for melting.



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Figure 5. AVAILABLE HEAT AS A FUNCTION OF PERCENT EXCESS AIR AND COMBUSTION AIR TEMPERATURE

At present, the trend in glass melting is toward reduced excess air in an effort to reduce energy consumption. Companies currently operate at approximately 6-8% excess air. In order to achieve this low level without increasing air pollutant emissions (carbon monoxide and hydrocarbons), operating procedures must be refined. One such refinement involves the use of proper burner positioning, which requires a device that allows for movement of the burners in very small increments. Work done on this refinement resulted in a reduction in excess air of 10%, from 18 to 8%, just by properly positioning the burners for optimum air-fuel mixing. At the same time, energy consumption decreased by 8%, and carbon monoxide and hydrocarbon emissions were maintained at acceptably low levels. Burner movements of 1 degree (the burners being rotated on an arc) were found to be significant in minimizing fuel

consumption, maintaining proper melting conditions, and controlling refractory temperatures. Burner positioning is one of the more important ways in which energy consumption can be controlled.

Furthermore, the glass industry is seeking to increase production rates without building new facilities. The most widely used technique is electric boosting. In this process, electrodes are pushed through the furnace walls below the glass surface. These electrodes supply heat directly to the already molten glass, causing an increase in stirring, which increases the heat transfer rate from the electrode to the glass. This system acts as an auxiliary source of energy on fuel-fired furnaces, which are restricted in the amount of fuel consumable because of regenerator and stack capacities. Thus, more heat is made available to melt the glass, and, consequently, more glass can be produced.

The net effect of electric boosting on energy consumption, if the energy consumed in electric generation also is considered, is an increase in the amount of energy used to melt a ton of glass. If, on the other hand, only the energy used directly for melting is considered, energy consumption per ton of glass melted usually is lower than that without electric boosting, although this will depend upon the input efficiency of the electric energy. Although there is no specific published information on electric consumption for boosting, 1.6-1.8 million Btu/ton of glass is the range most often quoted by companies that sell the equipment. Figures as low as 1.3 million Btu/ton are known. Because the theoretical energy requirement for melting glass is about 2.0 million Btu/ton and because only 1.6-1.8 million Btu of electric energy is consumed per ton of boost, additional energy must be used to make up the difference. Furnaces that utilize electric boosting do use more fuel, but the total energy consumption per ton of glass melted with electric boosting is still reduced.

For clarification of these points, the following example is presented. Consider a furnace capacity of 100 tons/day and a fuel efficiency of 6.25 million Btu/ton with no electric boost. The efficiency of this furnace is about 32%. Assume that the electric boosting system is designed to produce 5% of the total energy load of the furnace without electric boosting, or approximately 1.3 million Btu/hr. This assumption is reasonable according to one glass manufacturer. Assume a boost in production

of 24 tons/day. On this basis, the electric energy consumed is 1.3 million Btu/ton of boost. This is only 65% of the theoretical energy required to melt a ton of glass, and consequently, additional heat must be supplied in the form of additional fossil-fuel combustion, approximately 17 million Btu/day. However, fossil-fuel efficiency is only 30%; thus, the total additional fossil-fuel requirements are 57 million Btu/day. On this basis, the total energy consumed is 5.75 million Btu/ton of glass, a net reduction in energy consumption of 8%. This analysis assumes a 100% input efficiency of electrical energy, which is somewhat unrealistic. Table 2 shows the additional fuel requirements for the lower input efficiencies. This table also shows that net energy consumption per ton of glass increases if the input efficiency drops below 70%.

Table 2. ENERGY NEEDED PER ADDITIONAL TON
OF GLASS MELTED IN AN ELECTRICALLY
BOOSTED CONTAINER GLASS MELTER

Input Efficiency of Electrical Energy, %	Theoretical Energy	Electrical Energy Available	Supplemental Energy From Fossil Fuels*	Total
	10 ⁶ Btu			
100	2.00	1.3	2.33	3.66
90	2.22	1.3	3.07	4.37
80	2.50	1.3	4.00	5.30
70	2.86	1.3	5.20	6.50
60	3.33	1.3	6.77	8.07

* Energy from fossil fuel available at 30% efficiency to make up deficiency between 1.3 and 2.0 million Btu theoretical.

At this point, as previously described for electric melting, electricity generation also must be considered. Thus, the amount of energy consumed in generating the 1.3 million Btu of electric energy is 4.3 million Btu/ton of glass, and the total amount of energy consumed by this process increases to 6.33 million Btu/ton of glass melted, an increase of 1.3% over the case in which no electric boosting is used.

A second method for boosting production on a glass melter is oxygen enrichment, that is, the use of oxygen rather than air to burn the fuel. In this process, raw oxygen is mixed into the combustion air, thus increasing the percentage of oxygen in the air being fed to the flame. The hotter flame that is produced results in an increase in available heat for melting. As before, more available heat results in increased production. The energy consumed in producing the oxygen is less than 2.5% of the total energy required to melt a ton of glass and as such is not a factor. One advantage of this system over electric boosting is that the total energy consumption per ton of glass melted is reduced, whereas this is not necessarily true with electric boosting. The glass industry has not yet accepted this process as a means for boosting production; consequently, it is in very limited use at present.

The third method for boosting production is agglomerated batch. This method is gaining a great deal of attention in the U.S. not only as a means for boosting production, but also as a means for reducing air pollutant emissions from glass melters. However, batch agglomeration is not widely used in the U.S. because it is expensive to produce. Theoretical studies have determined that agglomerated batch should melt 2-3 times faster than normal granular batch. In Japan, undocumented increases of as much as 50% in production rates have been reported. In the U.S., several melting trials with agglomerated batch have been run, and in all cases, fuel consumption per ton of glass melted was reported to have decreased. In one instance, on a small 40 ton/day furnace, fuel consumption decreased by 1.0 million Btu/ton, from 7.5 to 6.5 million Btu/ton, when charged with agglomerated batch. Because furnace characteristics and operating practices vary so much from one glass plant to another and batch agglomeration is not an established practice, no generally applicable quantitative conclusions can be reached. However, agglomerated batch will increase production rates and fuel utilization efficiencies, even though it does require a considerable amount of energy to manufacture.

One very novel approach to melting glass is submerged combustion. In a submerged combustion melter, the burners are located in the bottom of the melter. The combustion gases pass through the glass bath, violently stirring the bath. At the same time, heat transfer to the batch from the gases is extremely efficient. Experimental work on a nonregenerative submerged combustion melter showed a reduction in fuel consumption of 50%. Although data are not available for regenerative submerged combustion melters, similar results are expected. The expected efficiency of such a furnace is high, perhaps 75%.

In spite of its advantages, submerged combustion melting is not used in the glass industry. One such furnace, however, is used as a premelter and reportedly still results in a saving of energy. One major problem of submerged combustion is that the product is molten glass filled with tiny air bubbles and therefore must be refined before it can be used. The time required for refining is quite long with present methods because the molten glass is so viscous. Solutions such as vacuum degassing have been suggested but have not been satisfactory. The problems of submerged combustion are of such severity that a commercially viable process is not expected to be available for another 10-15 years.

Energy Requirements of Annealing

Approximately 15% of the total energy consumed by the glass industry is for finishing operations, primarily annealing. Glass annealing lehrs are heated by convection, radiation, or a combination of the two. The most effective heating means is by zoned convection lehrs that have internal distributors to obtain lateral temperature uniformity. Unlike other types of lehrs, this design allows for interchangeability between natural gas and oil. Some lehrs are direct-fired by atmosphere or premix burners or by excess air burners. These lehrs generally are restricted to gaseous fuels.

Annealing lehrs in the glass industry generally operate at a thermal efficiency of only 20%. Much of the inefficiency is due to poor maintenance and operating practices. Most lehrs leak a considerable amount of unwanted cold air into their chambers or lose heated air through unwanted openings. However, little is done to improve annealing lehrs because their energy consumption is low and the possible results would not be worth the effort by the glass industry.

Air Pollutant Emissions in the Glass Industry

In addition to being the primary energy consumer in the glass industry, the glass-melting furnace also is the primary source of air pollutant emissions. The primary emissions are particulates, sulfur oxides (SO_x , sulfur dioxide and sulfur trioxide), nitrogen oxides (NO_x , nitric oxide and nitrogen dioxide), and carbon monoxide. Hydrocarbons are not a problem if proper combustion conditions are maintained. Table 3 summarizes emissions from various glass tanks across the country.

Factors Affecting Air Pollutant Emissions

Several factors influence the emission rate of particulates from a glass-melting furnace, including batch composition, batch preparation, and type of fuel. The production rate of the furnace also is a factor.

Measurements of stack emissions from a glass melter have shown that the particulates emitted are primarily sodium sulfate, which is a minor ingredient of most glass batch. In the furnace, it vaporizes and decomposes to form elemental sodium and sulfate.⁵ When these gases pass through the checkerbrick and are cooled, sodium sulfate is re-formed. Only about 40% of the sodium sulfate charged into the furnace is vaporized; the remainder goes into the glass. In addition to the sodium sulfate, a small amount of raw batch that is carried out of the furnace by the flue gases is emitted. This emission can be minimized by proper batch preparation, which consists primarily of wetting the material before charging it into the furnace.

The amount of SO_x emitted from a furnace depends on 1) the sulfur content of the fuel and 2) the amount of sulfur-bearing compounds in the raw materials. Consequently, natural-gas-fired furnaces generally exhibit lower SO_x emissions than oil-fired furnaces unless the sulfur has been removed from the oil. Measurements of SO_x emissions from a batch melter charged with batches with various sulfur contents showed a direct correlation between sulfur in the batch and SO_x emitted. The greater the sulfur content of the raw batch, the higher the SO_x emissions.

Table 3. AIR POLLUTANT EMISSIONS FROM
VARIOUS PRODUCTION GLASS MELTERS

Investigators	CO	NO _x	Particulates, lb/hr	Halogens	SO _x
	ppm	ppm		ppm	
1001 ²	35-50 ^a	490-700	6-8	1.0	28 ^e
Kyle and McMackin ⁴	0-5 ^b	450-600	--	--	--
Stockham ⁵	375 ^c	340	--	7.1	267
Arrandale ¹	--	--	2-10 ^d	--	--
Netzley ³	--	--	2-10 ^d	--	--

^a 8% excess air.

^b 25-45% excess air.

^c Excess air unknown.

^d Variable with production rate.

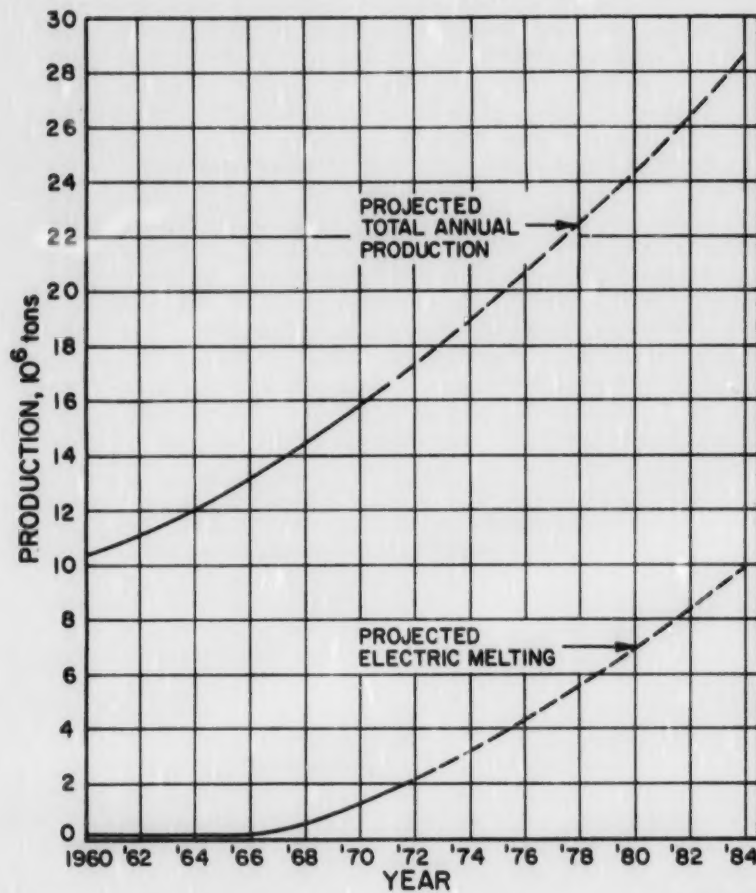
^e Natural gas fired.

The amount of NO_x emitted from a glass-melting furnace depends upon several factors, some of which are not understood. One important factor is flame temperature: NO_x formations in the furnace increase as flame temperature increases. For example, during a recently completed experimental program, NO_x emissions were measured during a complete firing cycle of a glass melter. NO_x emissions were highest at the beginning of the firing cycle and then, as the cycle continued, decreased by about 30%. At the beginning of the firing cycle the combustion air is preheated to a higher temperature, which results in a hotter flame than at the end of the cycle, when the checkerbrick and hence the air have cooled considerably. Other major factors in NO_x formation in a glass melter, such as flame velocity and recirculation patterns of flue gases, are being studied.

Other emissions, such as carbon monoxide and hydrocarbons, can be controlled easily with proper combustion conditions. If opal or green glass is being produced, halogens such as chlorine and fluorine also are emitted in very large quantities from a fossil-fuel melter. However, the industry has converted completely to electric melting, and this switch has eliminated these emissions.

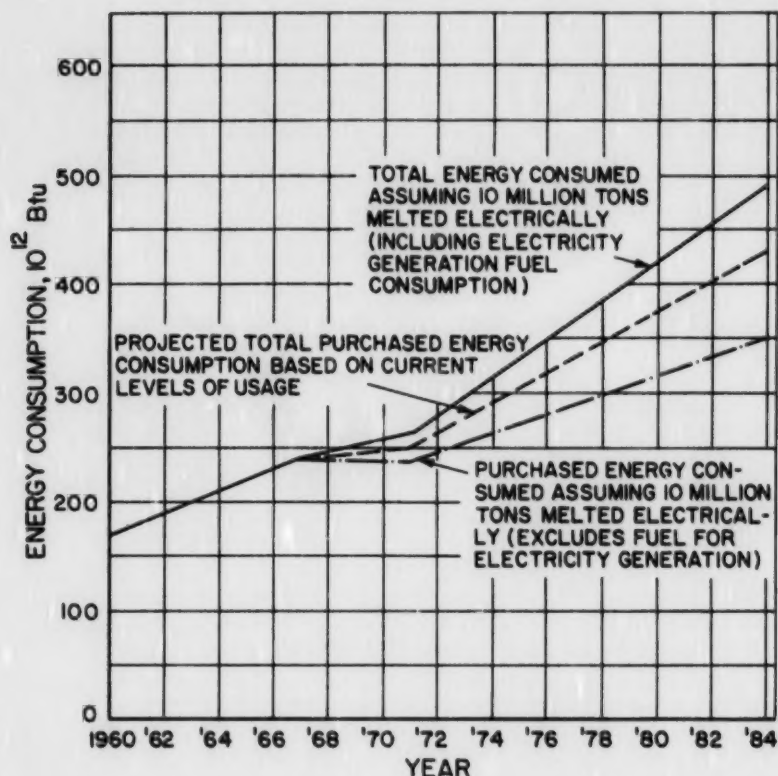
Effect of New Technology on Air Pollutant Emissions and Energy Usage

The major change in the glass industry during the next 8-10 years is projected to be a substantial growth in electric melting. Based on an extrapolation of the current growth rate (69% per year) of electric melting, by 1985 all melting would have to be done electrically. However, this is not a reasonable projection because electric melting growth was very rapid when just introduced but now is slowing down. Consequently, for the purpose of showing the effect of electric melting on energy consumption, a more reasonable projection has been assumed based on statements from the glass industry that electric melting growth will follow production growth. This more reasonable growth is shown in Figure 6. This projection indicates that, by 1984, 10 million tons of glass, or approximately one-third of total glass production, will be produced annually by electric melters. Based on this projection, energy consumption also was projected (Figure 7). These data show that by switching



A-83-1247

Figure 6. PROJECTED GROWTH OF TOTAL ANNUAL PRODUCTION COMPARED WITH AMOUNT PRODUCED ELECTRICALLY



A-64-923

Figure 7. EFFECT OF CONVERSION TO ELECTRIC MELTING ON ENERGY CONSUMPTION BY GLASS INDUSTRY

to electric melting, the total purchased energy consumed by the glass industry itself would decrease by about 18% over energy consumption based on current levels. However, if the amount of energy consumed to generate the electricity is included, based on a 30% efficiency of generation, total energy consumption would increase by 18%. Thus, in fact, the switch to electric melting will cause an increase in energy consumption nationally.

Electric melting has been gaining in usage because of its ability to reduce air pollutant emissions. Data on total emissions from glass plants are not available on a national basis; consequently, the effect of the projected increase in electric melting on air pollutant emissions cannot be determined quantitatively. Certainly, overall emissions would be reduced.

However, the emissions from the electricity-generating stations also should be considered. And on this basis, the net effect of electric melting quite possibly could be an increase in air pollutant emissions nationally.

By using new technology, significant reductions in air pollutant emissions can be obtained. Recently completed tests on agglomerated glass batch in a submerged combustion melter showed virtually no particulate emissions and very low NO_x emissions (Table 4).

Table 4. AIR POLLUTANT EMISSIONS FROM
SUBMERGED COMBUSTION MELTER

NO_x , ppm	34.5-48.7
SO_x , ppm	71-1210
Particulates, gr/SCF	
Loose batch	0.461-0.527
Agglomerated batch	0.0068-0.0150

The use of agglomerated batch prevents batch carry-over by the combustion gases out of the stack, so it should be beneficial in conventional melters as well. Submerged combustion reduces NO_x emissions because of its high efficiency in transferring heat away from the flame and to the glass itself. Consequently, a low-temperature flame is maintained, and NO_x emissions are substantially reduced. However, the product from a submerged combustion melter is foam glass, that is, glass with air bubbles, and is not acceptable for use in any product.

The use of oxygen enrichment of the combustion air as a means for boosting production and reducing energy consumption does not increase air pollutant emissions. Of particular concern in using oxygen enrichment is the possibility of an increase in NO_x formation due to a hotter flame. In fact, test results on a production facility showed no increase in NO_x emissions when the combustion air is enriched with 21-24% oxygen. Because the flame is theoretically hotter, heat transfer from the flame to the glass is much higher. Because more heat is transferred from the flame, the net effect is in reality a flame temperature comparable to that without oxygen enrichment. As a result, NO_x emissions do not increase.

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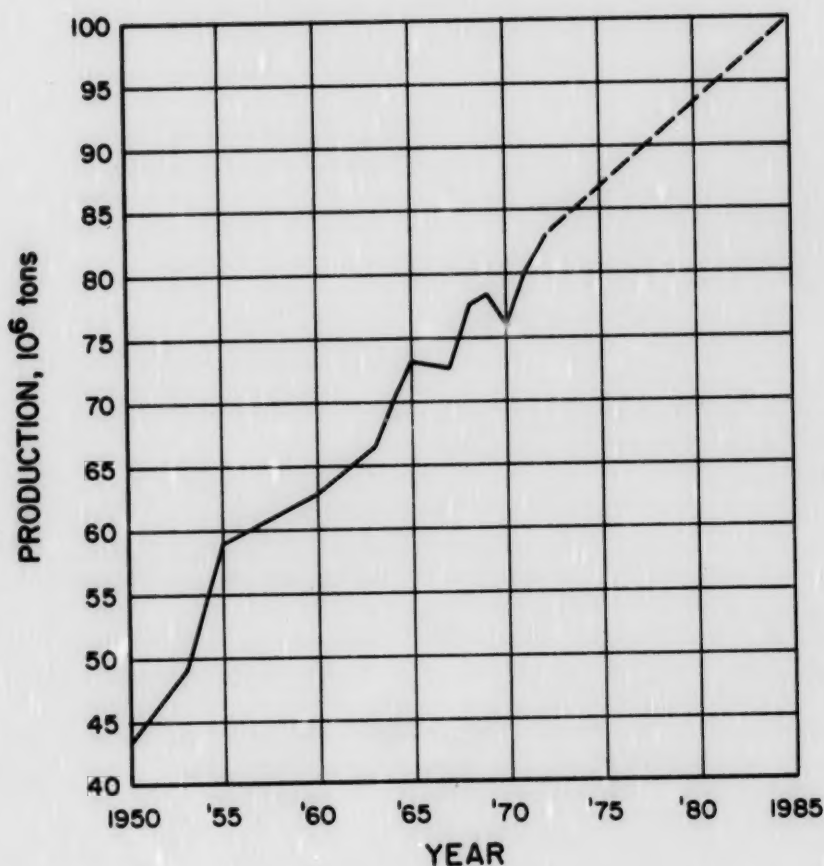
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VII. SIC CODE 324 - HYDRAULIC CEMENT

Summary

SIC Code 324 includes all establishments engaged in the manufacture of hydraulic cement, including portland, natural, masonry, and pozzolana cements. This report is limited to portland cement production because 95% of the cement manufactured in the U.S. is portland cement and the remaining 5% is split between the other types.

The cement industry has been growing at a steady rate of about 1.8% annually for more than 20 years, and this growth rate, which is shown in Figure 1, is expected to continue in the future.



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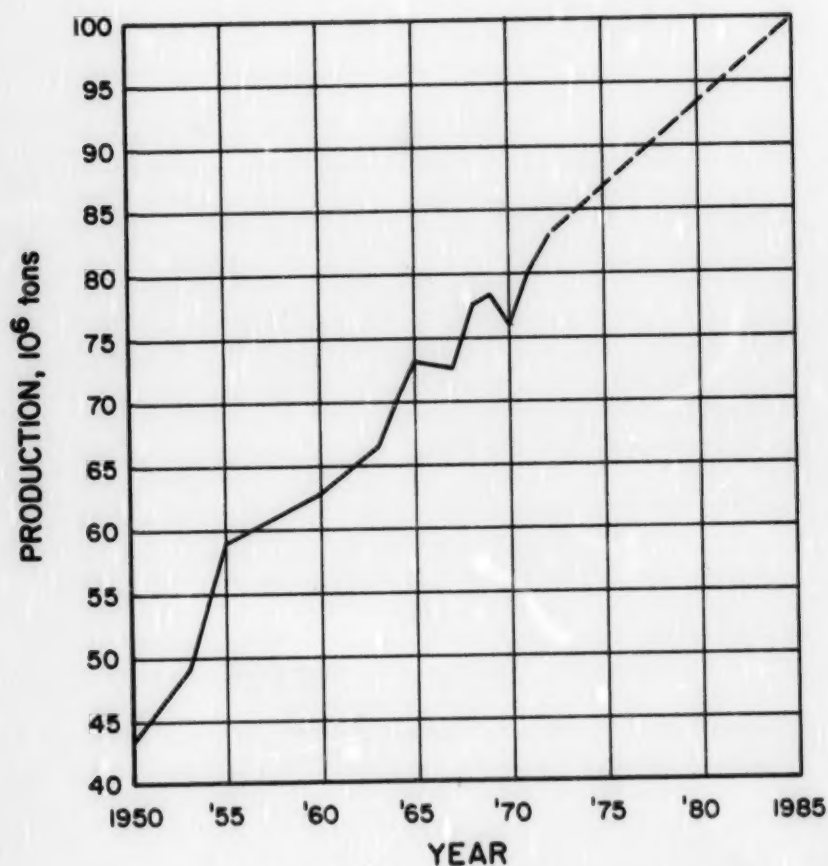
Figure 1. ANNUAL CEMENT PRODUCTION
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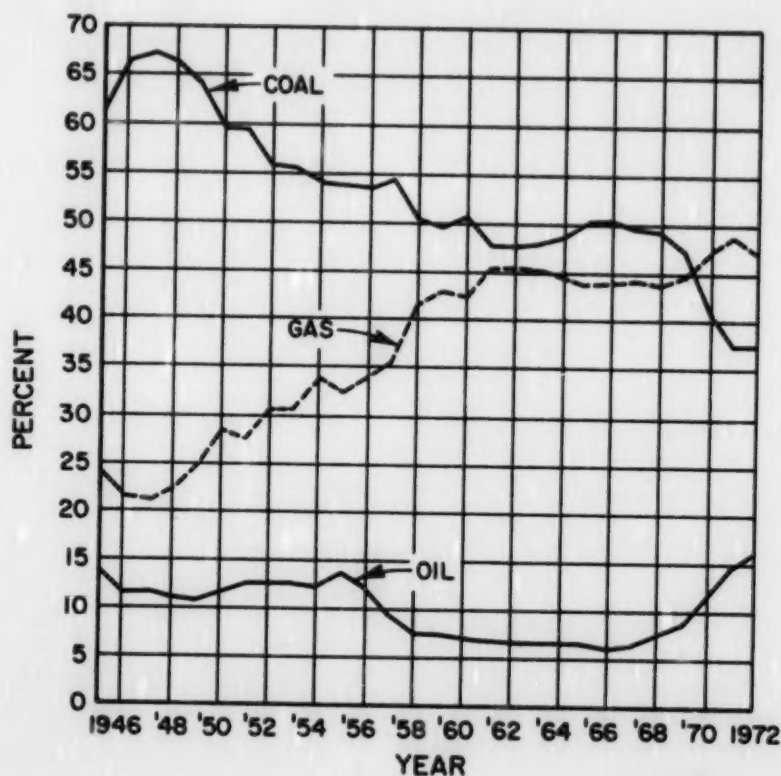
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Figure 1. ANNUAL CEMENT PRODUCTION
WITH PROJECTION TO 1985

Total cement production in the U.S. is estimated at about 83 million tons and is expected to reach 93 million tons by 1980.¹¹ The total amount of energy consumed by this industry in 1972 was about 581 trillion Btu, based on an average unit energy consumption of 7.0 million Btu/ton of cement produced. The primary sources of energy are natural gas, coal, and fuel oil. Figure 2, which breaks down energy consumption by type, indicates that coal and natural gas are used much more than fuel oil.



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Figure 2. FUEL USAGE OF U.S. CEMENT INDUSTRY⁷

However, a trend away from coal toward fuel oil has developed within the last 3 or 4 years, primarily because of the restrictions imposed by air pollution regulations.

In the short term (until 1985), air pollution regulations apparently will force this trend to continue. However, if fuel availability becomes a major problem, this trend is likely to reverse itself. In the long run, the implementation of new processes, particularly the vertical kiln, will tend to increase coal utilization. Although total annual energy consumption will increase as production increases, the unit energy assumption (i.e., Btu/ton of cement) will decrease as new process techniques are developed and implemented. In a modern, well-maintained cement plant that uses the latest available technology, fuel consumption can be reduced to less than 3.5 million Btu/ton of cement, about one-half of the current average consumption by the entire industry. On this basis, the industry average could reach 4.0 million Btu/ton of cement produced.⁷

The primary air pollutant emissions from the production of cement are particulates, SO_x , and NO_x . In general, particulate emissions can be controlled with collection devices capable of removing 99.8% of the particulates from an effluent gas stream. On the other hand, SO_x emissions are only partially controllable, and NO_x emissions are totally uncontrollable at present. Much of the air pollutant emissions from this industry are directly related to the type of fuel used; consequently, changes in the industry's fuel utilization pattern will directly affect air pollutant emissions. In particular, if the current trend away from coal as a fuel persists, particulate emissions will decrease, but this situation is readily reversible if a shortage of other, less polluting fuels develops and the industry is forced to revert to coal. SO_x emissions also depend on the type of fuels consumed and as such would be adversely affected in an energy supply shortage. In this case, however, although the industry might not be forced to burn coal, it might be forced to burn high-sulfur oil, in which case particulate emissions would be minimized, but SO_x emissions would increase. Under these circumstances, in the industry's attempts to deal with energy shortages and to reduce energy consumption by implementing new processes, both SO_x emissions and particulate emissions will increase.

Portland-Cement-Manufacturing Processes^{1-4,12}

Portland cement is made from a mixture of limestone and clay or similar materials. The raw materials first are ground and mixed together. Depending upon which of the two available processes is used, water is added during mixing (the wet process) or the ingredients are mixed dry (the dry process). In general, if the raw materials are moist to begin with, the wet process is used; likewise, the dry process is used if the raw materials are initially dry. The next step is the burning, or calcining, of the mixed material in a rotary kiln. This burning is done by heating the charge to approximately 2700°F to form the clinker, which is discharged from the kiln and subsequently cooled. The final step is the grinding of the clinker to the desired fineness. During this step, a small amount of gypsum (2-3%) is added to the clinker to control the setting time of the cement when wetted.

Raw Material Preparation

In preparation, the raw materials must be ground finely and mixed in the proper proportions. This step differentiates the wet from the dry process. In the wet process, the crushed raw materials are mixed with water and then ground up; the product is a slurry containing up to 50% water. The slurry is dewatered to about 20-30% water in a continuous separator. Basically, the separator is a large tank in which the solid material settles to the bottom. Water is drawn off the top, leaving a thickened slurry that is mechanically discharged at the bottom. The slurry then is transferred to the burning apparatus. In the dry process, the raw materials are simply ground and mixed together in the proper proportion; the material then can be charged to the kiln.

There was a time when one process might have been preferred over the other. Hard raw materials were used in the dry process, and soft materials were used in the wet process. Hard materials required that crushers and grinding mills be used to achieve the desired fineness, but the blending was difficult. The wet process was found to be the easiest and most economical way of producing the desired fineness of soft materials. Moreover, blending in a slurry is much easier. However, the equipment has improved such that either process can be used as desired.

The only energy consumed by this process is mechanically consumed in the operation of the crushers, grinders, and blenders. Previously, the dry process required more energy than the wet process because the power required for crushing and grinding the hard material was greater than the power required for washing the soft material and because the slurry was easier to blend than the dry raw meal. However, with the development of ball and tube mills, it became possible to grind hard materials with water at a 10-20% lower power consumption rate than without water.² Thus, the difference in power consumption between the two processes was minimized. Typically, preparation of the raw materials consumes about 600,000 Btu/ton of cement (2.0 million if electric generation is included). This energy is consumed as electrical energy, driving the crushers, grinders, blenders, and assorted conveyors. On this basis, approximately 8% of the total annual energy consumption, or 50 trillion Btu, is consumed in the preparation of the raw materials.

Burning the Raw Material³

Burning is the heating operation in which the raw materials combine chemically to develop a product with the desired hardening characteristics. Typically, the prepared raw materials are charged continuously into a cylindrical steel rotary kiln, turning at about 1 revolution per minute. The kiln, which is lined with firebrick, varies in diameter from 12 to 25 feet and in length up to several hundred feet. The kiln is mounted at an angle slightly off horizontal so that, as it rotates, the charge moves by gravity from the high, charging end to the low, discharging end. The discharge end of the kiln also is the firing end. The fuel used for firing can be natural gas, powdered coal, or, in some cases, fuel oil. After burning at 2700°F, the product, or clinker, is discharged and cooled so that it can be handled and stored. On the average, the burning process requires about 6.4 million Btu/ton of cement produced. Thus, in 1972, an estimated 530 trillion Btu of energy was consumed in the burning process.

In the burning process, the charge passes through three stages before being discharged. In the first stage, which begins as the load is charged into the kiln, the moisture is driven off. As the charge moves through the kiln, temperatures increase until, at about 1800°F, carbon dioxide is driven off. Finally, the charge moves through the hottest temperature zone, 2700°F, and burns. The resulting clinker is discharged and cooled.

Although the average energy consumption for burning is 6.4 million Btu/ton of cement, energy consumption varies from 3.7 to 9.0 million Btu/ton, depending upon many factors, such as chemical and mineral composition of the charge; particle-size distribution and fineness of the charge; diameter, length, pitch, and speed of rotation of the kiln; and efficiency of combustion and heat-recovery systems.⁵ Also, the wet process requires about 30% more energy for burning than the dry process, most of which is needed to vaporize the extra water.

Clinker Processing

After burning, the clinker is cooled and stored until needed. Basically, the only processing necessary is grinding the clinker to specification. This usually requires about 34,000 Btu of electric energy per ton of clinker ground, or 110,000 Btu if energy consumed for electric generation is included.

New Technologies in the Manufacture of Portland Cement

Several recent developments in the manufacture of portland cement have improved energy utilization. All the developments are centered around the burning process. To reduce the energy consumed in this process, the heat-transfer rate from the combustion gases to the charge must be increased.

Chain Systems³

In the first stage of the burning process, in which the raw materials are dried, several types of systems, including lifters to cascade the material through the combustion gases and plates and diaphragms to baffle the gases, have been developed to improve the heat-transfer rate over that which can be obtained in the plain cylindrical kiln. The method most used now is a system of chains hanging in the kiln.

In the wet process, the chains hang so that they dip into the slurry, thus becoming coated. As the kiln rotates, the chains emerge from the slurry, offering large-surface-area contact with the hot gases. Further down the kiln, in the second stage of the burning process, a system of festoon chains helps push the slurry and pug (nearly dried material) through the kiln. A well-balanced system of chains can reduce the temperature of the flue gases by about 350°F from the normal operation. Such a reduction in temperature means that more heat has been transferred to the load; i.e., less heat is escaping out of the stack.

In the dry process, temperatures are much hotter than in the wet process, resulting in the burning of the chains. To circumvent this problem, lifting devices are used to cascade the raw meal through the gases.

Preheaters³

A major advance in reducing energy consumption in the burning process was separating the first stage from the kiln and preheating the raw material up to near burning temperatures before it entered the kiln. The several ways in which this can be done are summarized in Table 1, which shows the effect of each method on energy consumption, assuming an average consumption for burning of 6.4 million Btu/ton by using current practice.

Table 1. ENERGY CONSUMPTION OF VARIOUS
CEMENT-MANUFACTURING PROCESSES³

<u>Process</u>	<u>Energy Consumption, 10⁶ Btu/ton</u>	<u>Reduction Over Average Current Practice, %</u>
Wet		
Long Kiln	5.94	--
Calcinator and Short Kiln	4.68	26.9
Semiwet		
Preheater and Short Kiln	3.60	43.8
Dry		
Long Kiln	4.68	--
Suspension Preheater and Short Kiln	3.15	50.8
Semidry		
Grate Preheater and Short Kiln	3.42*	46.6
Vertical Kiln	4.14*	35.3

* Includes 0.54 X 10⁶ Btu/ton for drying.

One method for preheating the raw material is to feed it dry, as a powder, into a series of cyclones in which it is heated by the hot combustion gases from the kiln. The hot raw material then is fed into a kiln that is shorter than would otherwise be used. This process is still considered to be a dry process, and the preheater is known as a suspension preheater. By using this system, energy consumption can be reduced by nearly 51% from the current industry average of 6.4 million Btu/ton.

The second method, referred to as the semidry process, involves wetting the raw materials to a moisture content of 12-14% and then nodulizing or pelletizing the material. The nodules or pellets then are fed onto a traveling grate, as a deep bed, through which hot gases are passed before the solids enter the kiln. Variations of both these methods have been developed and are widely used.

The energy savings in this process occur as the result of preheating the raw material and as a result of the improved rate of heat transfer that ensues when agglomerated raw materials are used. Agglomerating the raw materials enhances heat transfer by offering a uniformity in the materials through which the combustion gases pass, thus creating a more uniform flow distribution. In addition, agglomerated materials offer a greater amount of surface area for heat transfer, thus increasing its rate.

The energy saved by using this process is about 3.0 million Btu/ton of cement produced, compared with the industry average. In fact, the savings for this process and the process using the suspension preheater are slightly lower than stated because the energy consumed by a typical dry process is lower than the industry average.

In the wet process, developments have followed along the same lines. A preheater, known as a calcinator, that has been developed is separate from the kiln and consists of a rotating drum filled with heat-exchange bodies. Fuel consumption is reduced by 27% over the average fuel consumption of a normal kiln. The calcinator, in addition to reducing fuel consumption, increases the output when applied to existing kilns. Work is continuing to develop a way of reducing the water content of the slurry by filtration and, subsequently, producing nodules that then would be fed to a preheater. If this process were fully developed, further reductions

in energy consumption would be possible. At present, through the use of a complete series of batch-operated pressure filters, the moisture content can be reduced to 18-20%, but the product is difficult to handle and nodulize. However, the material is usable in deep-bed counter-flow preheaters and in traveling grate preheaters. This type of process is referred to as semiwet. Potential energy savings of 44% exist.

Vertical Kilns

The vertical kiln is not a new concept in cement technology, but when it was first introduced about 75 years ago, its performance was unsatisfactory.⁹ It was unable to produce cement of consistently good quality; fluctuations in strengths, setting, and soundness properties of the cement were very high. However, the vertical kiln has seemingly been developed such that these problems have been solved. Satisfactory performance of the vertical kiln requires that the raw materials be dampened and nodulized prior to being fed into the kiln. It also requires the use of low-volatile fuels, such as coal. In the vertical kiln, the nodules and fuel are fed continuously into the top of the kiln, and the clinker is extracted, cold, from the bottom by a rotating grate. Fuel consumption in a vertical kiln is about 3.6 million Btu/ton of clinker, more than 40% less than the average fuel consumption of rotary kilns (6.4 million Btu/ton). Further development is expected to reduce this figure to 2.6 million Btu/ton.⁹

One disadvantage of the vertical kiln is that its capacity is limited to about 300 tons/day.³ A number of vertical kilns in a row, however, require less space and cost much less than a rotary kiln of corresponding capacity,⁹ so output capacity is not really a problem.

Oxygen Enrichment

Much work has been done in recent years to determine the feasibility of enriching the combustion air of a rotary kiln with oxygen to increase production and reduce fuel consumption. One such program used oxygen lancing, a technique in which the oxygen is introduced directly into the combustion chamber, rather than being introduced into the combustion air fan and mixed with the air. The use of oxygen resulted in a maximum

production rate 40% higher than the rate with no oxygen; in addition, fuel consumption per ton of product decreased by 15%. (See Figure 3.⁸)

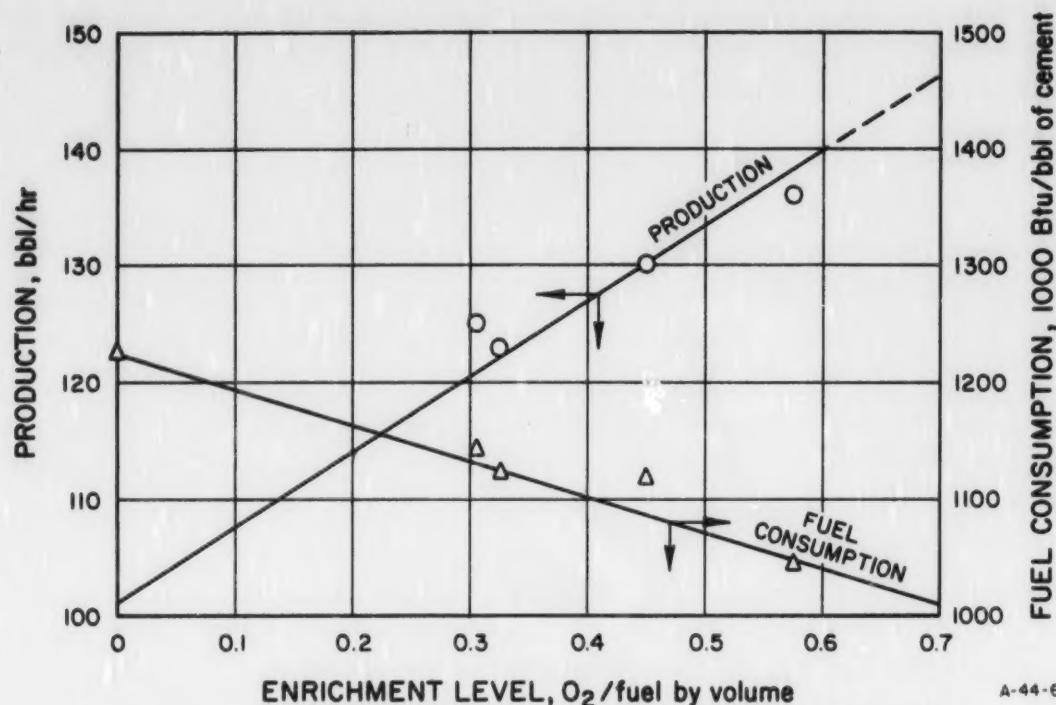


Figure 3. PRODUCTION AND FUEL CONSUMPTION IN ROTARY KILN VERSUS OXYGEN ENRICHMENT LEVEL⁸

Another program with oxy-fuel burners achieved good results.⁶ In spite of its technical success, oxygen enrichment is not used in U.S. cement plants. The major deterrent is that the cost of oxygen is too high and cannot be justified, at present, by the improvements in efficiency. However, if the same results can be produced at lower oxygen consumption rates, or if fuel availability to this industry becomes severely restricted, this process might be more realistic. Otherwise, only a drastic reduction in oxygen costs would bring this process into use by the industry.

Cement Production Without Heat¹⁰

Aside from all the techniques for reducing fuel consumption in rotary kilns or other heating devices, one process has been developed for producing cement without heat treatment. Certain clays can be strengthened by treatment with small amounts of lime to produce cementitious products similar to those formed by hydration of portland cement. This occurs

through the slow reaction of lime with the alumina silicates of clays. The only energy consumed is power for a specially designed grinder and mixer that can accelerate the rate of strength development of the mixtures. The process uses a wide variety of available materials and can produce a wide range of products. Although this process was designed for use in underdeveloped areas, the fact that waste products such as flyash, rice hulls, and siliceous mining wastes can be converted to cementitious materials through a relatively simple process should make it attractive to industrialized countries as well. At present, a pilot plant is being planned to determine, among other things, the economic factors associated with this process.

Other Concepts

One concept that has been developed recently is the use of a submerged combustion burner that operates while submerged in the cement mix. Although the burner was originally used in a rotary kiln, the technology has been developed for use in a trough kiln. The trough kiln is divided into a preheating zone and a calcining zone. In the first zone, waste-heat gases from the calcining and clinker-cooling processes are introduced under pressure through a high-temperature porous media, thereby fluidizing the mix for conveying through the sloped stationary kiln into the calcining zone, where the mix is fluidized and calcined by the submerged combustion burners. The fully calcined mix then is discharged into a short rotary kiln, in which clinkering occurs. Based on experimental laboratory data, the heat requirements for this system are about 2.7 million Btu/ton of cement. At this fuel consumption rate, a 58% savings in fuel over the current average consumption rate would be realized.

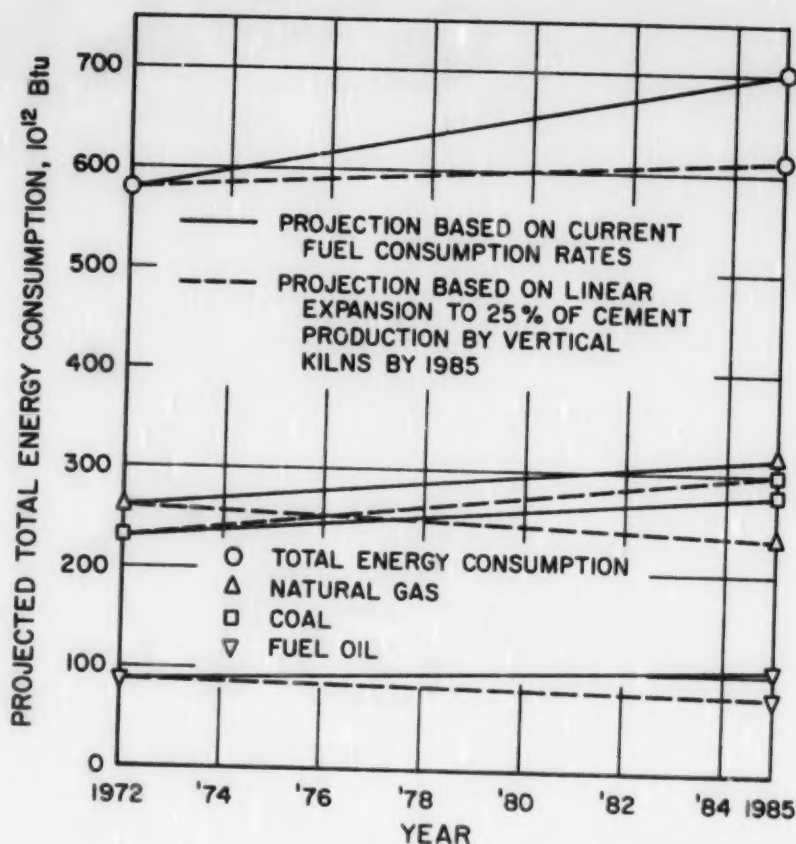
Other stationary systems have been developed, but, as yet, they are unproved. Consequently, there are no definitive operating data. The advantage of a stationary system is the capacity for fully automatic process control instrumentation; such a capability significantly enhances the operating efficiency. Automated process control has limited applicability in a rotary kiln.

Energy Utilization Pattern

Although no revolutionary changes have occurred in portland cement manufacture during the last 60 years, the evolutionary changes that have occurred have improved efficiency and reduced fuel consumption. However, the industry in the U.S. apparently is not taking advantage of these changes. While the rest of the world's cement producers are switching from the wet process to the dry process, which consumes less energy per unit production, the U.S. producers have been staying with the wet process.

There are two reasons for this trend. First, the dry process requires slightly more manpower than the wet process. Second, fuel has been cheap in the U.S. Consequently, more attention has been focused on saving labor costs than on saving fuel costs. This trend is beginning to reverse itself, however, because possibilities for increasing production capacity with little or no extra investment in equipment are better in modern dry-process kilns and fuel prices are beginning to increase.

At present, approximately 45% of the energy consumed by the cement industry is natural gas, 15% is fuel oil, and 40% is coal. Wide acceptance of the vertical kiln by the cement industry would cause a marked shift away from natural gas and toward coal. Figure 4 shows that if the cement industry were to switch 25% of the projected production load from rotary kilns to vertical kilns by 1985, total energy consumption would be about 12% less than if current energy consumption levels were maintained. Furthermore, natural gas consumption would decrease by nearly 10% from its current level and would be 25% lower than if the current ratios of gas-to-coal-to-oil consumption were maintained through 1985. At the same time, under current fuel ratios, total annual coal consumption would be 22% higher in 1985 than in 1972, and if the projected shift to vertical kilns were to take place, total coal consumption would only be 6% higher in 1985 than if no shift had occurred, or a total of 30% higher than in 1972. With a switch to vertical kilns, total oil consumption would be 26% lower than current projected levels.



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Figure 4. EFFECT OF CONVERSION OF ROTARY TO VERTICAL KILN BY CEMENT INDUSTRY ON ENERGY UTILIZATION PATTERNS

The energy consumed per ton of cement produced can be expected to decrease in the future, and most of the methods used to reduce consumption will center around the kiln as the major area for significant energy savings. In the short term (prior to 1985), energy consumption by the kiln process can reasonably be expected to decrease from 6.4 to 4.7 million Btu/ton. Figure 5 summarizes the concepts for reducing energy consumption in the short term on the typical rotary kiln. If all these concepts were implemented to the maximum extent possible and if the industry were to switch over to the dry process, the reductions in energy consumption stated above would be realized. The figures given after each concept in Figure 5 are the reductions in energy consumption that

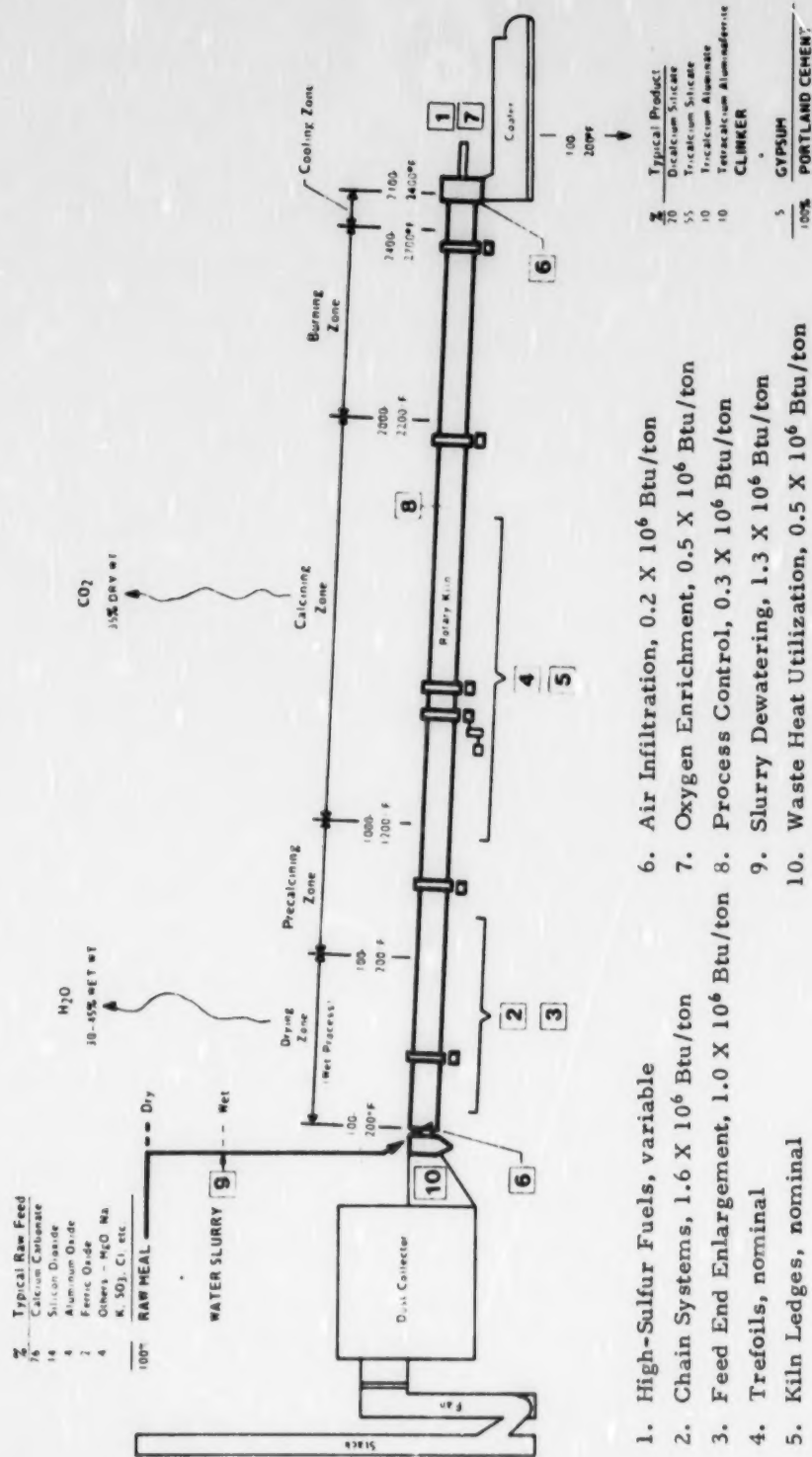


Figure 5. SHORT-TERM ENERGY-SAVING CONCEPTS
IN THE U.S. CEMENT INDUSTRY⁷

have actually been achieved. However, these reductions are not cumulative; that is, implementation of all these concepts would not reduce energy consumption by 5.4 million Btu/ton, the summation of savings realized by implementation of each individual concept.

In the long run, after 1985, reductions in energy consumption to below 3.5 million Btu/ton should be expected. Most of the reductions will be a result of the implementation of new kiln processes, primarily the vertical kiln and suspension preheaters in combination with short rotary kilns. The rate of implementation will depend on the economic climate, but the industry is not expected to be able to amass the necessary capital for converting to these new processes until 1985.

Air Pollutant Emissions From Cement-Manufacturing Processes

The major air pollutant emission problem in the manufacture of portland cement is particulates, which occur in all phases of cement manufacturing from crushing and raw material storage, to clinker production, to clinker grinding, storage, and packaging. However, emissions also include the products of combustion of the fuel used in the rotary kilns and drying operations; these are typically NO_x and small amounts of SO_x . Table 2 summarizes the emissions from cement-manufacturing processes without controls.

The largest source of emissions in cement plants is the kiln operation. At present, about 56% of the cement kilns in operation use the wet process, and 44% use the dry process. Based on this information, estimates of total emissions from cement plants in 1972 are given in Table 3. These estimates, because of a lack of data, assume the use of no controls by the industry, and without an inventory of equipment in use, they cannot be refined.

Most efforts to control air pollutant emissions focus on particulates because they are not only the greatest problem but also the easiest to control. The most desirable method of control is to collect the dust and recycle it by injecting it into the burning zone of the kiln, thus converting it to clinker. However, because of the high alkali content of the dust and its potentially bad effects on product quality, only a limited amount of dust can be recycled.

Table 2. EMISSION FACTORS FOR CEMENT MANUFACTURING WITHOUT CONTROLS (Ref. 13)^{a, b}

Pollutant	Dry Process		Wet process	
	Kilns	Dryers, grinders, etc.	Kilns	Dryers, grinders, etc.
Particulate ^c				
lb/ton	245.0	96.0	228.0	32.0
kg/MT	122.0	48.0	114.0	16.0
Sulfur dioxide ^d				
Mineral source ^e				
lb/ton	10.2	-	10.2	-
kg/MT	5.1	-	5.1	-
Gas combustion				
lb/ton	Neg ^f	-	Neg	-
kg/MT	Neg	-	Neg	-
Oil combustion				
lb/ton	4.2S ^g	-	4.2S	-
kg/MT	2.1S	-	2.1S	-
Coal combustion				
lb/ton	6.8S	-	6.8S	-
kg/MT	3.4S	-	3.4S	-
Nitrogen oxides				
lb/ton	2.6	-	2.6	-
kg/MT	1.3	-	1.3	-

^aOne barrel of cement weighs 376 pounds (171 kg).

^bThese emission factors include emissions from fuel combustion, which should not be calculated separately.

^cTypical collection efficiencies for kilns, dryers, grinders, etc., are: multicyclones, 80 percent; electrostatic precipitators, 95 percent; electrostatic precipitators with multicyclones, 97.5 percent; and fabric filter units, 99.8 percent.

^dThe sulfur dioxide factors presented take into account the reactions with the alkaline dusts when no baghouses are used. With baghouses, approximately 50 percent more SO₂ is removed because of reactions with the alkaline particulate filter cake. Also note that the total SO₂ from the kiln is determined by summing emission contributions from the mineral source and the appropriate fuel.

^eThese emissions are the result of sulfur being present in the raw materials and are thus dependent upon source of the raw materials used. The 10.2 lb/ton (5.1 kg/MT) factors account for part of the available sulfur remaining behind in the product because of its alkaline nature and affinity for SO₂.

^fNegligible.

^gS is the percent sulfur in fuel.

Because of the complications of kiln burning and the large volumes of gases and materials that are handled, several dust collection systems have been developed. Depending upon the temperature of the effluents and the emission standards of the community, the industry uses mechanical collectors,¹⁵ electrical precipitators,¹⁶ baghouse filters,¹⁷ or combinations of these devices to control emissions. Typically, in treating the flue gases from the kiln operation, mechanical separators are normally

Table 3. ESTIMATED TOTAL EMISSIONS
FROM CEMENT PLANTS IN 1972

<u>Pollutant</u>	<u>Dry Process</u>			<u>Wet Process</u>		
	<u>Kilns</u>	<u>Dryers, etc.</u>		<u>Kilns</u>	<u>Dryers, etc.</u>	<u>Total</u>
Particulates, tons	4.5 X 10 ⁶	1.8 X 10 ⁶		5.3 X 10 ⁶	0.7 X 10 ⁶	12.3 X 10 ⁶
Sulfur Dioxide, tons*	0.19 X 10 ⁶	--		0.24 X 10 ⁶	--	0.43 X 10 ⁶
Nitrogen Oxides, tons	0.047 X 10 ⁶	--		0.060 X 10 ⁶	--	0.107 X 10 ⁶

* Does not include emissions due to sulfur in fuel because these numbers depend on the sulfur content of the fuel, which is variable.

required ahead of either precipitators or glass bag collectors. However, wet-process kilns, which have lower exit-gas temperatures than dry-process kilns and relatively high moisture in the exit gases, are commonly followed directly by the precipitators because the moisture contributes to more satisfactory precipitator operation.¹⁴

Efficiency of particulate removal depends upon the types and combinations of equipment used. Typically, multicyclone filters have an efficiency of 80%, and electrostatic precipitators have an efficiency of 95%. A combination of electrostatic precipitators and cyclones has an efficiency of 97.5%. Fabric filters (baghouses and the like) operate at a 99.5% removal efficiency. From this information, adequate equipment for particulate control apparently is readily available.

SO_x emissions result from burning the raw meal in the kiln. There are two sources of emissions in the kiln: sulfur in the raw material and sulfur in the fuel. The amount of sulfur present varies from plant to plant and with geographic location. Most of the sulfur dioxide emissions are inherently controlled in the process of cement manufacturing because about 75% of the raw feed is converted to calcium oxide, which reacts with sulfur dioxide. In addition, the presence of sodium and potassium compounds in the raw material aids in the direct absorption of sulfur dioxide into the product. However, the variable chemistry and operating conditions in U.S. cement plants affect the amount of sulfur dioxide entrapment and, in some cases, the quality of the product. Sulfur dioxide entrapment of this type seems to be about 75% in those plants for which data are available.⁷ Sulfur dioxide also is removed by this same mechanism in baghouse filters, in which the sulfur-dioxide-laden gases contact the collected cement dust. The degree of control by sulfur dioxide absorption depends upon the alkali and sulfur content of the raw materials and fuel.

Effect of New Technologies on Air Pollutant Emissions

The implementation of new processes in the cement industry could result in an increase in air pollutant emissions, even if current control devices continue to be used. The most serious problems are likely to occur with implementation of the vertical kiln because of the potential for increases in both SO_x and particulate emissions. These emissions

would result from the increase in coal utilization due to implementation of the vertical kilns. However, the sulfur dioxide absorption rate might be higher because of the intimate contact between reactants, in which case SO_x emissions could conceivably be lower than current emission rates. Whether or not particulate emissions increase will depend on the control methods used.

The use of oxygen enrichment, because it increases flame temperature, may tend to increase NO_x . However, oxygen enrichment has been used in other industrial processes in a similar manner and NO_x emissions did not increase.* NO_x emissions probably will be reduced if the vertical kiln becomes widely used. Although there are no data on NO_x emissions from vertical kilns, the absence of a high-temperature flame, which favors NO_x formation, tends to support this claim.

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VIII. SIC CODE 325 - STRUCTURAL CLAY PRODUCTS

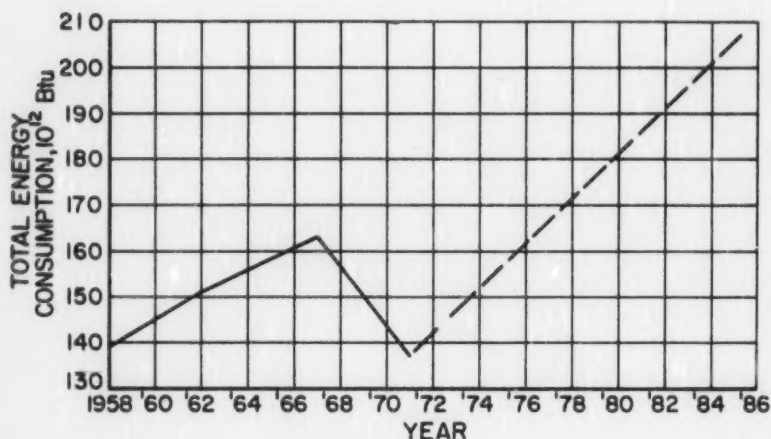
Summary

The structural clay products industry comprises establishments engaged in the manufacture of brick and structural clay tile, ceramic wall and floor tile, clay refractories, and miscellaneous items such as adobe brick and clay sewer pipe. Establishments engaged in the manufacture of china, earthenware fittings, bathroom accessories, kitchen articles, and porcelain electrical supplies are classified in SIC Code 326. By comparison, the latter establishments consume about one-sixth as much energy as establishments covered by SIC Code 325.

This report section covers several types of ceramic products with widely differing manufacturing processes and end uses. In addition, the units of production depend on the product being manufactured; production is reported in single units, thousands of units, thousands of dozens of units, short tons, and so on. (The dollar value of shipments is not used in this report because it is constantly fluctuating, making comparisons from one year to the next difficult, if not impossible, without a complex economic evaluation.) Consequently, general statements about the industry, as well as comparisons between sectors of the industry, cannot readily be made.

During the past 15 years, this industry has been very stable, increasing in annual production at only about 1% per year. Consequently, total annual energy consumption has tended to increase only slightly. (See Figure 1.) In 1971, energy consumption did decrease, but this was due ostensibly to a temporary decrease in construction, where many of this industry's products are used.

The primary sources of energy consumed by this industry are natural gas, manufactured gas, still gas, coke-oven gas, blast-furnace gas, fuel oil, coal, and electricity. About 97% of the energy consumed is for direct process heat in the firing of kilns and dryers. The remaining 3%, practically all of which is electricity, is consumed in the drives for the grinders, conveyors, and blenders. This report covers only the direct heating processes because most of the energy is consumed here and the greatest possibilities for significant reductions in energy consumption exist here.



A-54-822

Figure 1. TOTAL ENERGY CONSUMED BY THE STRUCTURAL CLAY PRODUCTS INDUSTRIES⁸

The industry as a whole is sensitive to the economy and tends to grow at nearly the same rate as the economy. Thus, total energy consumption is likely to increase only very slowly. No dramatic changes that could affect energy consumption by the industry are expected in the future. However, a slight trend toward automatic processing and shorter firing cycles that is developing will reduce the energy consumed per unit of production. Because of the diversity of this industry, the size of this reduction is difficult to assess.

Structural-Clay-Manufacturing Processes

Although the large number of products manufactured by this industry require different raw materials, different firing temperatures and cycles, and different types of machinery for each operation, the basic sequence of operations is very similar for all products. First, the raw materials, which are usually various clays and other minerals, including soda ash, kaolins, magnesite, and dolomite, are crushed and ground to the required mesh size. Next, the material is mixed with water in a pug mill or blunger. When the material is of the proper consistency, it is formed into various shapes by any number of methods, such as casting, pressing, or extrusion, and subsequently dried. The next step is firing, which is usually done in kilns at temperatures from 1500⁰ to 3000⁰F, depending on

the product. For products requiring glazing, an additional firing cycle is required, but for those requiring no glazing, the manufacturing is complete after one firing cycle.

Drying^{1,5}

The first major energy-consuming process in the manufacture of structural clay products is drying the green product after it has been formed. Four methods are used for drying: rack drying in the open or in open sheds, hot floor, drying rooms, and tunnel dryers. Of these methods, drying rooms and tunnel kilns are most commonly used because they provide the shortest drying times. Air-drying, which is certainly the cheapest method, also is the slowest method, generally too slow for modern production operations. In addition, air-drying requires more handling than other methods, subjecting the ware to dirt, possible damage, and moisture pickup from the atmosphere. Consequently, its use is limited.

Hot floor dryers, drying rooms, and tunnel dryers are typically heated by direct-fired air heaters, exhaust heat from tunnel kilns and gas turbines, steam coils, and infrared heaters. Of these methods, direct firing with auxiliary fuel is the most desirable because it allows for the most complete control over the drying process. The waste gases from the kilns are also used with supplementary firing, but only if doing so does not disrupt the draft in the kiln. Waste warm air from the cooling section of a kiln is especially desirable because it is not diluted with combustion gases from the kiln, thus reducing the chance of contamination by carbon or sulfur. Compared with steam coil drying, direct firing can usually produce hotter drying air with a smaller sized dryer, accomplishing faster drying with less floor space.⁵

Infrared heaters, although used, are ineffective for drying and removing moisture unless blowers are used for circulating the air through the ware. An alternative to this system is a recirculating air heater, which is cheaper to operate and requires a lower capital investment than the infrared heating system.

Steam coils are used to heat air for the dryer, but because many boilers and steam coil systems are limited to low-pressure operation, the coils do not get hot enough to do a very fast job of drying. Boilers used for this purpose are either fired with auxiliary fuels, or they utilize waste heat from the firing kilns.

Because of the diversity of this industry, no figures on the energy consumed by the drying process are published, nor are there any statistics on the usage of the different drying methods.

Firing²

Three basic types of kilns are used to fire the dried ware: field kilns, beehive kilns, and tunnel kilns. Of these types, tunnel kilns are preferred for plant efficiency, manpower requirements, and product quality.

Tunnel kilns are large car-type kilns that fire the product continuously. Ware is loaded up on refractory-topped cars or, in the case of low-temperature applications, on conveyor belts and continuously pushed through a continuously heated tunnel. Ware entering the tunnel is gradually heated by waste heat circulated from the cooling section at the exit of the kiln. The preheated ware is pushed into the firing zone, where it is heated to the desired maturing temperature. The fired material then is pushed into the cooling zone by incoming cars loaded with ware, where heated air is removed and channeled back to the kiln entrance for preheating. Natural gas is the most common fuel used for firing large tunnel kilns, although coal, fuel oil, and on occasion electricity may be used.

Beehive kilns are large, round downdraft kilns that are operated on a discontinuous basis; thus, they also are termed periodic kilns. With this type of kiln, ware is placed inside, fired to the desired temperature, cooled, and then removed. During firing, the combustion gases circulate to the roof of the kiln and then down through the ware to exhaust ports in the floor. One advantage of this type of kiln is that the temperature gradient is nearly eliminated, compared with straight updraft kilns. Another advantage is that this type of kiln can be fired when required and can be used for a wide range of heavy clay products. But therein also lies its major drawback. In a periodic kiln, the ware is set and the kiln fired. At the end of the firing cycle, the kiln is allowed to cool for ware removal. This results in a tremendous waste of heat and consequently in high fuel consumption rates.

Historically, these kilns have been fired with coal, but in recent years these kilns have been switched to oil and natural gas firing.² One trend has been the use of instrumentation and automatic controls to improve fuel economies and reduce labor costs. Fuel economies also have been achieved with insulating firebrick linings, steel encasements, and use of insulating refractory concretes for crowns, flues, arches, and firebox sidewalls.

Another type of periodic kiln is known as a chamber kiln; it is used primarily in Europe. In these kilns, chambers are located in a circular or oval shape and alternately loaded, fired, cooled, and unloaded as the firing zone is moved around the kiln. Waste heat from the cooling sections is used to preheat the ware ahead of the firing zone. Although these kilns are not as thermally efficient as tunnel kilns, they are a large improvement over the beehive kilns.

Energy Utilization Pattern

The pattern of energy utilization within this industry, other than the total fuel consumption by type, is very difficult to assess because no definitive figures exist on the fuel consumption rates of specific processes. Different firing times and temperatures are required for different types of products. Figure 2 shows the effect of temperature on energy consumed by both tunnel kilns and periodic kilns for various types of ware. For bricks fired in chamber or tunnel kilns, energy consumption varies from 400 to about 3250 Btu/lb. But without specific information relating the product mix to firing temperatures, process energy consumption cannot be quantified for the industry as a whole.

Nevertheless, certain trends that do exist within the industry have implications for energy consumption patterns in the future. The first trend is a noticeable switch away from periodic kilns to continuous kilns. Figure 2 shows that periodic kilns typically consume about twice the amount of energy that tunnel and chamber kilns consume at comparable temperatures. Such a shift means that the average energy consumption per unit of production should decrease in the future. The second trend is toward increased automation of the entire production from grinding of the raw material to firing of the ware. The expected reduction of rejected ware also will reduce energy consumption. A third trend that is developing is a shift away from steam-drying to direct-firing.

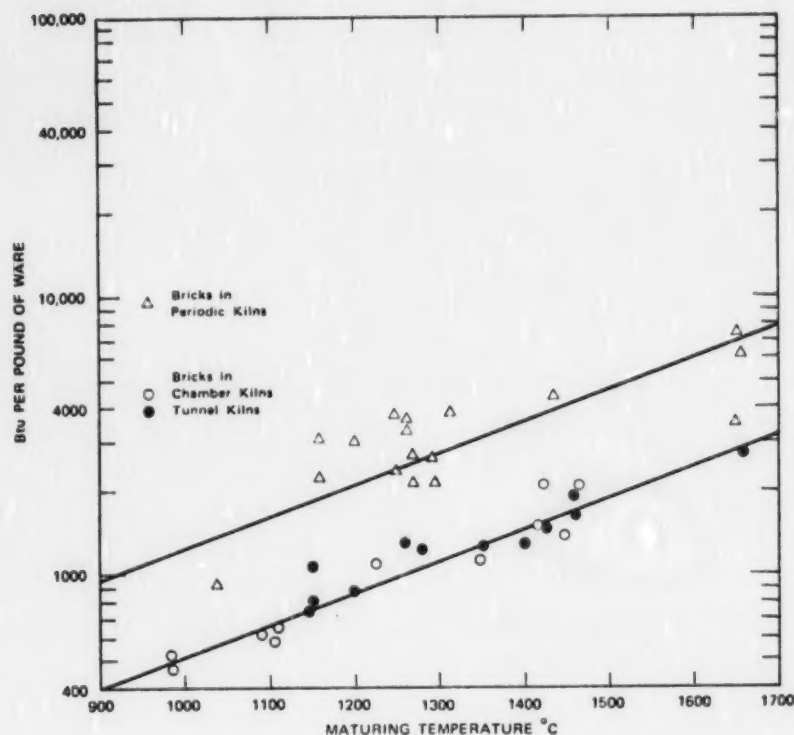


Figure 2. HEAT UNITS REQUIRED FOR FIRING
IN THE CERAMIC INDUSTRY⁷

In general, the industry is striving to reduce energy consumption by reducing the length of firing cycles and lowering firing temperatures when possible. The new firing techniques that have been developed are discussed later in this section.

It is difficult to say, with any accuracy, what changes will occur in the types of fuels that are used. At present, between 60 and 70% of the energy consumed in this industry in the U.S. is gas (a combination of natural, manufactured, still, blast-furnace, and coke-oven gas) because of the color requirements of the ware and the clean burning characteristics of the gas. However, a large part of this load could be transferred to oil or coal. Glaze-firing or certain special cases in which controlled atmospheres are required would seem to be the only major exceptions.

New Technologies and Their Effects on Energy Consumption

Although this industry is slow to change, some new firing techniques that have been developed reduce the energy consumed per unit of product by kilns. One such technique, applicable to both tunnel kilns and periodic kilns, is the use of high-velocity jet-firing.^{4,6} The use of jet burners improves several aspects of the firing operation by supplying the necessary movement of the gases in the kiln to eliminate problems of heat stratification, improve temperature uniformity, and provide for better control of the kiln atmosphere. The jet burners enable the use of smaller kilns, resulting in lower heat losses through the kiln sidewalls and improving fuel efficiency. Information on the extent of the improvement in fuel efficiency is not available, but a fuel consumption rate of 500 Btu/lb of standard 8-inch three-hole brick at 2550°F (1400°C) has been reported for tunnel kilns.⁶ This fuel consumption rate appears at the low end of the curve in Figure 2 and thus would appear to represent a substantial improvement over current practices, perhaps as high as a 50% reduction in fuel consumption.

A second technique that has been developed is forced-draft firing in periodic kilns.³ A major portion of the fuel in a natural-draft kiln is spent for heating the kiln so that an adequate draft is established. In fact, the proper kiln conditions may require several days to achieve. However, forced-draft firing systems drive hot, dry air through the kiln long before a draft would be available, resulting in a significant decrease in kiln time. Forced-draft firing also eliminates problems normally associated with windy days. With a forced-draft firing system, the kiln can be made to operate under slightly pressurized conditions, virtually eliminating any effects of the wind on the kiln operation. Experiments on various beehive kilns indicate that production can be increased by 25%, firing time reduced by 30%, and fuel consumption per unit of production reduced by 20% by switching to a forced-draft firing system.

Air Pollutant Emissions

Emissions from structural-clay-manufacturing processes are primarily particulate matter, although other pollutants, including SO_x , carbon monoxide, and fluorides, also are emitted. Table 1 summarizes the emissions from the various processes. The data show that particulate emissions are most severe during the handling of the raw materials. All the other emissions occur during the firing of the ware.

Several factors are involved in the emission rates of the various pollutants. Particulate emissions are affected by the type of grinding (wet or dry), the kiln temperatures, the gas velocities, and the flow direction of the gases in the kiln. Gaseous emissions are affected by the composition of the clay being processed and by the fuel being used to fire the kilns. Of primary concern are the SO_x and the fluorides. Both of these gases are emitted as a result of the presence of sulfur and fluorides in the clay. In addition, sulfur results from the type of fuel being consumed; the amount that is emitted (as SO_x) depends upon the sulfur content of the fuel. Other gaseous emissions that pose problems are NO_x and carbon monoxide, both of which are formed during combustion. NO_x formation is not entirely understood, but higher flame temperatures are known to increase NO_x formation. Carbon monoxide usually is formed as a result of incomplete combustion of the fuel due to insufficient combustion air or incomplete mixing of the fuel and air. Coal, because it is a solid fuel, is more susceptible to incomplete combustion than the other fossil fuels.

Methods of controlling emissions are similar to those used in other industries. Cyclone filters used in conjunction with scrubbers can reduce particulate emissions by 90%. Bag filters and electrostatic precipitators also can be used effectively. Both SO_x and fluorides can be removed from the effluent gases by a variety of scrubbing techniques, but the cost is nearly prohibitive.

Table 1. EMISSION FACTORS FOR STRUCTURAL-CLAY
MANUFACTURING WITHOUT CONTROLS (Ref. 9)^a

Type of process	Particulates		Sulfur oxides (SO _x)		Carbon monoxide (CO)		Hydrocarbons (HC)		Nitrogen oxides (NO _x)		Fluorides (HF)	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Raw material handling												
Dryers, grinders, etc.	96	48	-	-	-	-	-	-	-	-	-	-
Storage	34	17	-	-	-	-	-	-	-	-	-	-
Curing and firing												
Tunnel kilns												
Gas-fired	0.04	0.02	Neg ^b	Neg	0.04	0.02	0.02	0.01	0.15	0.08	1.0	0.5
Oil-fired	0.6	0.3	4.0S ^c	2.0S	Neg	Neg	0.1	0.05	1.1	0.55	1.0	0.5
Coal-fired	1.0A	0.5A ^d	7.2S	3.6S	1.9	0.95	0.6	0.3	0.9	0.45	1.0	0.5
Periodic kilns												
Gas-fired	0.11	0.05	Neg	Neg	0.11	0.05	0.04	0.02	0.42	0.21	1.0	0.5
Oil-fired	0.9	0.45	5.9S	2.95S	Neg	Neg	0.1	0.05	1.7	0.85	1.0	0.5
Coal-fired	1.6A	0.8A	12.0S	6.0S	3.2	1.6	0.9	0.45	1.4	0.70	1.0	0.5

^a One brick weighs about 6.5 pounds (2.95 kg). Emission factors expressed as units per unit weight of brick produced.

^b Negligible.

^c S is the percent sulfur in the fuel.

^d A is the percent ash in the coal.

Examination of techniques being applied by the structural clay industry to reduce fuel consumption leads to the conclusion that emission rates affected by combustion (as opposed to clay composition) will tend to decrease in the future. Possible exceptions are NO_x emissions, which may increase because of the utilization of higher operating temperatures, and particulates, which may increase because of an increase in kiln gas velocities, causing an increase in dust pickup from the load.

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IX. SIC CODE 331 - BLAST FURNACES, STEEL WORKS AND ROLLING AND FINISHING MILLS

Summary

The energy used in blast furnaces, basic steelmaking processes, and various reheating processes, which include rolling and finishing (all of which are encompassed by SIC Code 3312), amounts to more than 18% of the total energy consumed by industry in the U.S. In 1971, this amounted to more than 3000 trillion Btu of primary energy, excluding the energy consumed for electricity generation.² Tables 1 and 2 show the breakdown of primary fuel utilization in the industry.

Table 1. CONSUMPTION OF ELECTRICITY
BY THE IRON AND STEEL INDUSTRY*

<u>Year</u>	<u>Consumption, 10¹² Btu</u>
1971	166.03
1970	169.22
1969	165.16
1968	157.53
1967	145.09

* Excludes fuel consumed for generation.

However, the industry also consumes large amounts of secondary fuels, that is, tar and pitch, coke-oven gas, and blast-furnace gas, as shown in Table 3. These fuels are not included in the total energy consumption figure because they are by-product fuels from processes consuming the primary fuels. (See Figure 1.) By 1985, steel production is expected to approach 200 million tons/yr, and energy consumption is expected to reach 4100 trillion Btu/yr.²⁶ This is a 65% increase in production and a 28% increase in energy consumption between 1971 and 1985.

The most significant changes in energy consumption by this industrial sector will occur in the ironmaking and steelmaking processes. In ironmaking, the most significant factor will be the increase in coke rates to the blast furnace if the supply of hydrocarbon fuels used for injection does not diminish. By 1985, coke rates are projected to be approximately 0.5 ton/ton of pig iron produced, a reduction of about 20% from current practice.²⁶ However, such a reduction in coke rates will produce a

Table 2. CONSUMPTION OF PRIMARY FUELS BY THE
IRON AND STEEL INDUSTRY, 1967-1971

Purpose	1967	1968	1969	1970	1971
Fuel Oil, 10 ¹² Btu					
Blast Furnace*	12.16	14.44	20.03	24.82	30.99
Steelmaking	84.97	82.26	75.54	62.39	44.69
Heating/Annealing	60.39	55.12	47.01	56.52	51.51
Other	30.19	40.33	42.72	41.19	39.26
Total	187.71	192.15	185.30	184.92	166.45
Natural Gas, 10 ¹² Btu					
Blast Furnace*	51.78	54.35	53.42	56.66	52.01
Steelmaking	88.95	105.75	95.70	59.83	48.15
Heating/Annealing	287.07	311.30	349.17	316.86	340.75
Other	125.45	139.09	158.55	181.04	183.81
Total	553.25	607.49	656.84	614.39	624.72
Coal, 10 ¹² Btu					
Blast Furnace*	2166.82	2128.76	2202.63	2285.01	1960.39 [†]
Steelmaking	--	--	--	--	--
Heating/Annealing	--	--	--	--	--
Other	180.23	177.52	154.41	132.83	121.24 [‡]
Total	2347.05	2306.28	2357.04	2417.84	2081.63
Total Primary Fuels, 10 ¹² Btu					
Blast Furnace*	2230.76	2197.55	2276.08	2366.49	2043.39
Steelmaking	173.92	188.01	171.24	122.22	92.84
Heating/Annealing	347.46	366.42	396.18	373.38	392.26
Other	335.87	353.94	355.68	355.06	344.31
Total	3088.01	3105.92	3199.18	3217.15	2872.80

* Includes coke-oven underfiring.

† Includes conversion to coke.

‡ Includes steam generation.

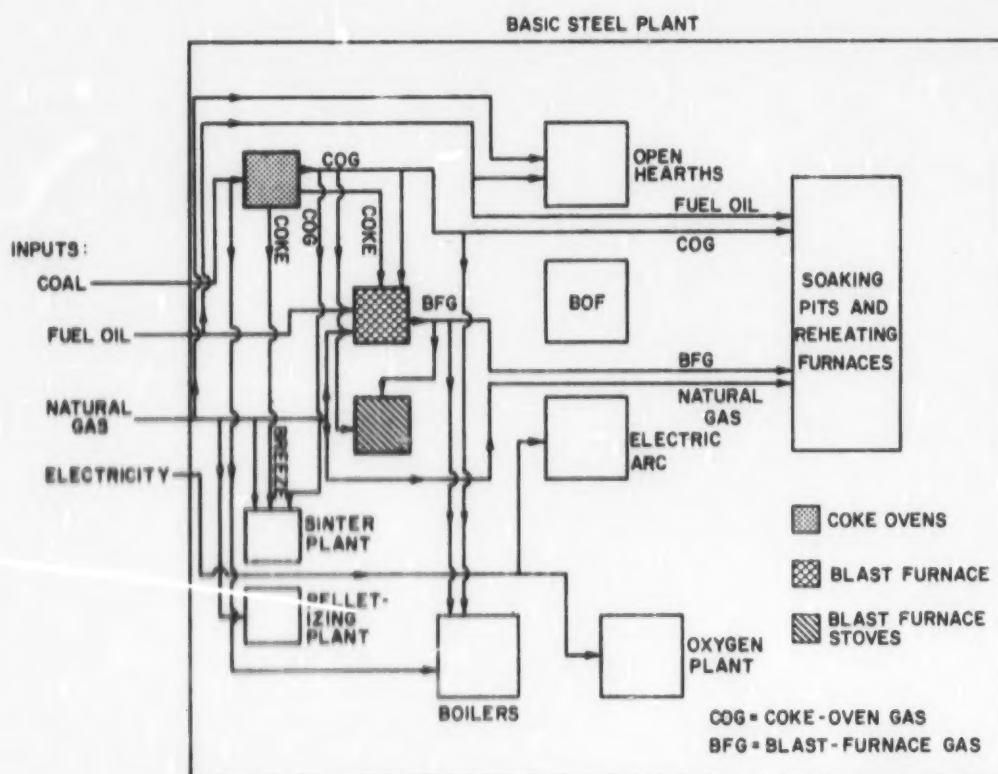


Figure 1. TYPICAL ENERGY UTILIZATION PATTERN FOR BASIC STEEL PLANT

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deficit of in-plant-generated coke-oven gases currently used elsewhere in the plant as a heating source. As a result of this deficit alone, the use of purchased fuels will increase. In steelmaking, the most significant factor in the reduction of total energy consumption will be the phasing out of the open-hearth process and its replacement with the basic oxygen process. Based on 1971 energy consumption data, this will result in a 4% reduction in energy consumption (approximately 124 trillion Btu annually). However, this does not take into account the energy used to manufacture the oxygen.

Energy Utilization Background Information

Ironmaking Processes

Iron Ore Preparation

The first step in the manufacturing of steel is the refinement of iron ore to pig iron, a process that is carried out primarily in a blast furnace. (Direct reduction, in which iron ore is directly converted

Table 3. SECONDARY FUELS CONSUMED BY
THE IRON AND STEEL INDUSTRY

<u>Purpose</u>	<u>1967</u>	<u>1968</u>	<u>1969</u>	<u>1970</u>	<u>1971</u>
Tar and Pitch, 10 ¹² Btu					
Blast Furnaces*	3.35	3.66	6.94	6.80	2.75
Steelmaking	39.72	34.89	32.89	28.30	17.76
Heating/Annealing	--	--	--	--	--
Other	5.40	3.18	2.45	6.64	6.93
Coke-Oven Gas, 10 ¹² Btu					
Blast Furnaces*	145,177	138,843	153,340	164,402	153,431
Steelmaking	16,381	16,400	14,973	11,028	6,546
Heating/Annealing	176,118	179,684	189,014	181,949	161,970
Other	100,596	99,257	94,190	104,479	111,079
Blast-Furnace Gas, 10 ¹² Btu					
Blast Furnaces*	255,679	270,610	290,086	269,698	244,773
Steelmaking	--	--	--	--	--
Heating/Annealing	15,475	15,717	17,596	15,645	15,439
Other	121,290	136,774	144,236	144,328	126,956

* Includes coke-oven underfiring.

to steel, is discussed later.) The iron ore (burden) is charged into the blast furnace in one of three conventional forms: crushed and screened, sintered, or pelletized. In terms of energy consumption by a blast furnace, a pelletized charge is preferable because it requires less energy than raw ore that has only been crushed and screened. The desirable characteristics of a pelletized or sintered burden over a raw ore burden are as follows:

- The burden's porosity is increased for easier penetration of the reducing gases.
- The more uniform particle size distribution of the burden results in better gas flow patterns in the blast furnace.
- Undesirable materials in the burden, such as iron ore dust and gangue, are minimized.

The use of agglomerated materials also increases the production rate of pig iron from the blast furnace while reducing the energy consumption per ton of pig iron produced.⁹ With agglomerated material, the flow patterns of the blast through the burden are more uniform, and the slag rate is reduced. Figure 2 shows that a 30-40% increase in

production rate occurs when the amount of agglomerates charged increases from 1000 to 2900 lb/net ton of pig iron.

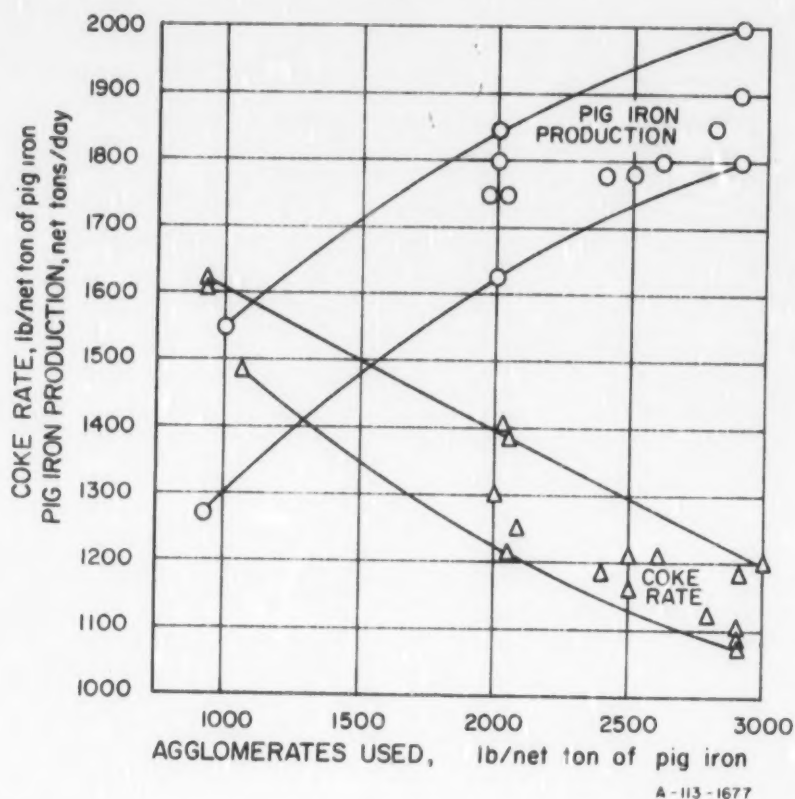


Figure 2. EFFECT OF BURDEN AGGLOMERATION ON BLAST FURNACE PRODUCTION RATE AND COKE RATE

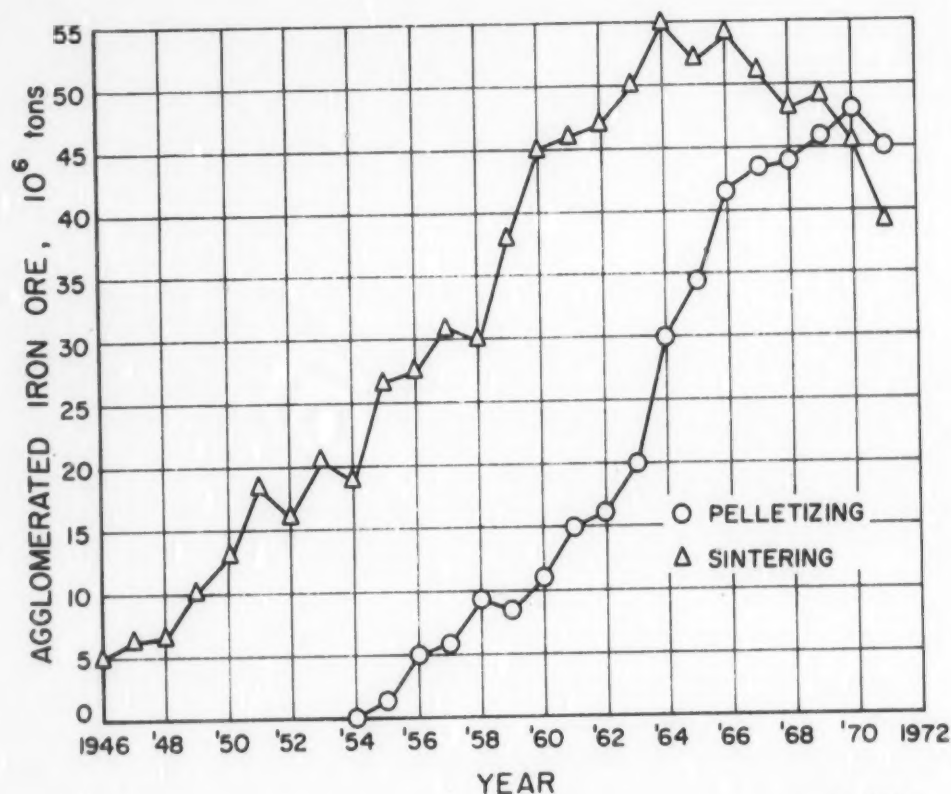
Over the same range, the coke rate decreases approximately 25-30%. However, such a decrease in the coke rate will produce a similar decrease in the production of coke-oven gas. For example, from 1959 to 1971, coke production decreased at the rate of approximately 27 lb/ton of pig iron/year. The manufacturing of 1 ton of coke produces approximately 14,000 CF of coke-oven gas, or roughly 7 million Btu. Thus, because of the reduced coke production, approximately 100,000 Btu of coke-oven gas/ton of pig iron is not produced. Furthermore, blast-furnace-gas production is reduced at the rate of 70 CF, 66.50 Btu/lb of coke, and the calorific value of the gas that is produced is lower. For every ton of coke produced, 20 million Btu of by-product gas is no longer available. In 1971, 21.9 trillion Btu less by-product gas was produced on this basis than in 1970. Consequently, this loss of in-plant energy

must be replaced by other purchased fuels, such as natural gas and fuel oil, and this must be carefully considered in an energy projection.

Sintering

Sintering is a process in which iron ore fines, mill scale, flue dust, coke breeze, and water are mixed and processed through a traveling-grate sintering furnace.¹⁶ The coke breeze supplies most of the energy needed, but 160,000 Btu of other energies (coke-oven gas, etc.) per ton of sinter is required for ignition of the bed.¹ In 1971, about 39.5 million tons of material was sintered, and the amount of energy consumed for ignition alone was 6.32 trillion Btu.

Sintering processes have been in use for nearly 30 years. However, the production of sinter has been decreasing steadily during the last 8 years (Figure 3).



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Figure 3. ANNUAL CONSUMPTION OF AGGLOMERATED MATERIALS IN U.S. BLAST FURNACES

Sintering plants usually consume energy in the form of blast-furnace, coke-oven, and natural gas for ignition and coke breeze for primary heat. Because of their ready availability within the blast-furnace plant, blast-furnace gas and coke-oven gas traditionally have supplied most of the energy consumed for ignition. But within the last 3 or 4 years, natural gas usage has increased such that it is being used for ignition in the production of more than 60% of the sinter, partly because of the decreasing availability of in-plant gases caused by the reduced coke production in the blast furnaces.

Figure 3 shows that the use of sintering as a means of burden agglomeration is decreasing in favor of pelletizing, a trend that is expected to continue. The use of natural gas for ignition will continue to increase, if available, although fuel oil can be used.

Pelletizing

Pelletizing is similar to sintering in that beneficiated fine iron ore is formed into wet "green" balls, which are fired in a furnace at 2000⁰-2400⁰F. Normal fuel requirements are approximately 600,000 Btu/ton of pellets produced.¹ In 1971, 45 million tons of pellets were produced, consuming a total of 27 trillion Btu.²

The production of pellets for use in blast furnaces started in 1954. By 1958, pellet production was about 10 million tons. Since then, the use of pellets has increased rapidly, quadrupling in 10 years.² Energy consumption also has increased fourfold.

Approximately 75% of the fuel consumed in the production of pellets is natural gas, and the remaining 25% is fuel oil.¹ Coke-oven gas and blast-furnace gas, although technically suitable for this process, are not used because pelletizing usually is carried out at the iron ore mine or on route to the mill. It is economically more attractive to ship pellets to the mill rather than raw ore.

The use of pellets is expected to continue to increase, primarily because air pollution from pelletizing plants is less than that from a sinter plant. As air pollution standards become higher, pelletizing might grow at an even faster rate than in the past. A second reason for the trend to more pelletizing is that the process overall consumes less energy than the sintering process because it is significantly more efficient on a thermal basis (75%, compared with 10% for sintering). The shift from sintering to pelletizing also depends upon changes in coke-oven operation, which have reduced the availability of by-product coke-oven breeze as a fuel.

As the use of pellets increases, so too will total energy consumption of purchased fuels (natural gas and fuel oil). The type of fuel used will depend upon cost and availability and not on interchangeability because both gas and oil can be used for firing the furnaces.

Blast-Furnace Operation

After the iron ore has been suitably prepared (crushed or agglomerated), it is charged into a blast furnace for chemical reduction to pig iron. The blast furnace is the single largest consumer of energy in steelmaking, consuming approximately 42% of the total energy used by the steel industry.

In the blast-furnace process, iron-bearing materials (including sinter, pellets, raw iron ore, mill scale, slag, and iron or steel scrap) are charged into the top of the furnace together with fuel (coke) and fluxes. Heated air (blast) is blown into the bottom of the furnace. In some cases, auxiliary fuels, such as gas, oil, or powdered coal, are also blown in. The blast air burns with part of the coke and also supplies sensible heat to produce the total heat required for the chemical reactions and for melting the iron ore. The balance of the fuel and part of the off-gas from the combustion remove the oxygen combined with the metal through chemical reaction. Typically, an input to the furnace of 1.6 tons of iron-bearing materials, 0.65 ton of coke, 0.25 ton of limestone or dolomite, and 1.8-2.0 tons of air produces an output of 1.0 ton of iron, 0.2 to 0.4 ton of slag, 0.05 ton of flue dust, and 2.5-3.5 tons of blast-furnace gas.¹⁶ These quantities change slightly, depending upon the type of burden used. The molten iron is removed at temperatures around 2700°F and transported directly to the steelmaking process or cast into "pigs."

The production of pig iron has been increasing in proportion to the demand for steel, as expected. Figure 4 shows the annual production of pig iron in the U.S. from 1947 to 1971.²

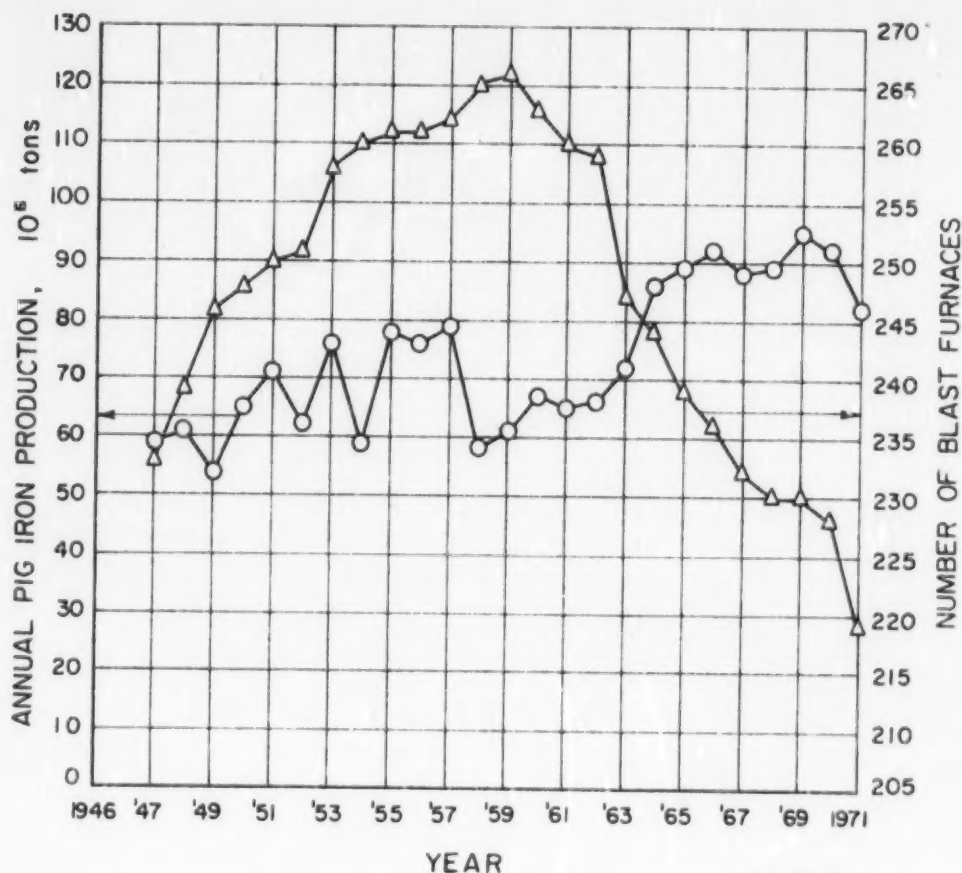


Figure 4. ANNUAL BLAST-FURNACE PRODUCTION IN TERMS OF BLAST FURNACES IN OPERATION

Only since 1969 has pig iron production decreased, but this is due to the decrease in the demand for steel. Figure 4 also shows the number of blast furnaces in operation in January of each year. These data indicate that individual blast-furnace capacities have increased by about 65% since 1947.

The primary source of energy in blast-furnace operation is coke. (The coking process is discussed later.) Coke has two functions in the production of pig iron: First, it produces the heat required for smelting, and second, it supplies the chemical reactants (primarily carbon monoxide) required for reducing the iron ore. The carbon monoxide is formed by reaction of the oxygen in the hot blast with the carbon in the coke. However, the coke also supplies the carbon that dissolves into the hot metal (about 80 lb/ton of pig iron). Approximately 80% of the reduction in the furnace is due to the carbon monoxide; the remaining 20% is accounted for by the strong reducing capabilities of the incandescent carbon in the coke.¹⁶

During the last 10 years, the amount of coke required to produce 1 ton of iron has been steadily decreasing (Figure 5). In 1961, 1440 pounds (0.72 ton) of coke were required to produce 1 ton of pig iron. By 1971, coke consumption had decreased to 1250 pounds (0.625 ton) per ton of pig iron, approximately 14%.² Among the reasons for this decrease in consumption are increased blast temperatures, hydrocarbon fuel injection, and improvements in burdens. The single most important factor is probably the rapid conversion to pelletizing throughout the industry. Figure 5 shows that coke consumption decreased rapidly from 1959 to 1966 and then stabilized after 1966. Figure 3 shows that the use of pellets increased significantly from 1960 to 1966, correlating well with the reduction in coke consumption.

During the past few years, the use of auxiliary fuels to produce hydrogen, which reduces iron oxides faster than carbon monoxide, also has become widespread in the industry. Between 1967 and 1971, the amount of fuel oil used in blast furnaces increased threefold from 67 to 194 million gallons.² During this same period, the amount of natural gas injected remained constant, even though it is by far the easiest fuel to inject.

The primary reason for injecting auxiliary fuels (fuel oil, natural gas, coke-oven gas, and tar) into the blast furnace is to reduce the coke rate. On an economic basis, coke consumed in the blast furnace is the largest single item of conversion cost in the steel industry. In general, the deciding factor on which fuel is used for injection is economics.¹⁵

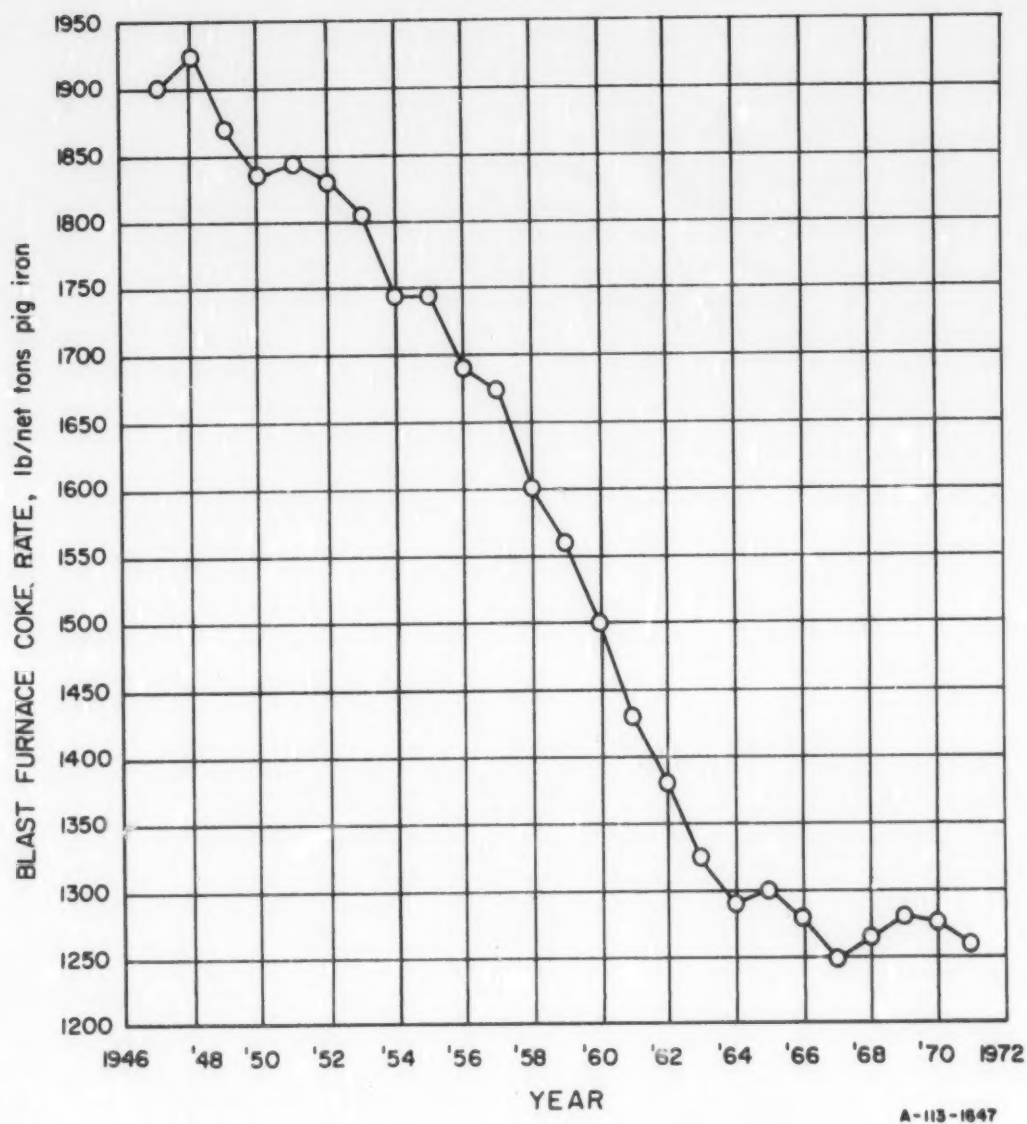


Figure 5. AVERAGE BLAST FURNACE COKE RATE

The fuel that is least expensive in the region in which the steel plant is located is the fuel used. In terms of operating results with fuel injectants, there is little difference between fuels other than in the blast temperature required to maintain operation.

The energy equivalent of hydrocarbons typically injected ranges from 0.5 to 2.5 million Btu/ton of iron; the calculated average is about 1.5 million Btu/ton of iron.¹ Based on the 1971 statistics of hydrocarbon fuels injected into blast furnaces, approximately 58% of the iron produced in blast furnaces was accomplished by using hydrocarbon injection, using approximately 70 trillion Btu. The potential for consumption of energy by hydrocarbon injection was 120 trillion Btu in 1971.

Production output from a blast furnace also is directly related to the wind rate, that is, the rate (CF/min) at which the blast is blown into the furnace. Higher wind rates produce higher production rates. Injection of oxygen into the blast serves the same purpose as increasing the wind rate and consequently is referred to as "equivalent wind." Oxygen injection has no significant effect on coke rate, yet 6% oxygen added to the blast can increase productivity by 30% and more (Figure 6).^{14,25} However, oxygen injection is not widely used because of problems with temperature control and generally questionable economics.

By 1985, iron production for use in steelmaking is projected to be about 130 million tons, based on a 200 million ton steel production, of which 35% is scrap. This production level is approximately a 65% increase over that in 1971. Assuming that energy consumption per ton of iron produced remains constant, total energy consumption by this process will increase by 65%.

Blast-Furnace Stoves

Another energy-consuming process in the production of iron is the heating of the blast air in blast-furnace stoves prior to blowing it into the blast furnace. Prior to 1950, blast-air temperatures were usually below 1200°F, but with the realization that higher blast-air temperatures increase production rates, blast-air temperatures of 1400°-2000°F now are more common. In general, the fuels used to heat the blast air are blast-furnace gas and coke-oven gas, primarily because of their ready

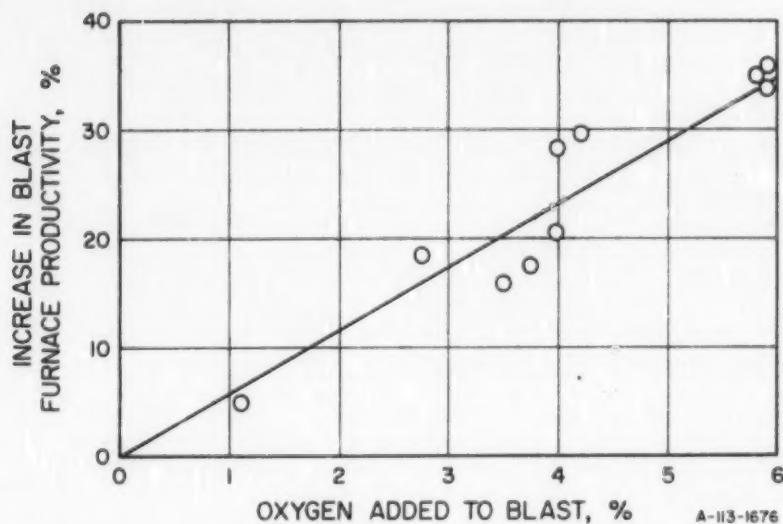


Figure 6. EFFECT OF OXYGEN INJECTION TO BLAST ON BLAST FURNACE PRODUCTIVITY

availability. The amount of energy consumed by a blast stove depends upon its efficiency and the temperature to which the blast is being heated. Typically, the efficiency of a blast-furnace stove is about 75%. However, as the desired blast temperature increases, the efficiency decreases because of increased heat losses in the form of higher flue gas temperatures. If the efficiency is assumed to be 75% and the desired blast temperature 1300°F, the amount of energy required to heat the blast is 2.25 million Btu/ton of iron produced.¹ In 1971, blast furnace stoves consumed 180 trillion Btu of energy. Based on average operating data from all U.S. furnaces using higher blast temperatures and other operating improvements, for an increase in blast temperatures from 1250° to 1550°F, coke rates decreased from 1600 lb/ton of pig iron to 1250 lb/ton of pig iron, while pig iron production increased from 1050 to 1600 tons/day. The coke replacement ratio has been determined to be 20 pounds of carbon for every 100°F increase in blast temperature.

Coke Ovens

The manufacturing of metallurgical coke is the primary consumer of coal in the steel industry. Coke is produced by the destructive distillation of coal. Two processes for coking are known: the beehive process and the by-product process. However, the beehive process has been phased out of production in the U.S., mainly because of the stringent air pollution legislation in effect and because of a lack of coals suitable for use in the process.¹⁶

The by-product process uses the combustion of gases external to the coke ovens to supply the heat required for distillation. The primary gases used for this process are coke-oven gas and blast-furnace gas. When higher production rates are desired, small amounts of high-Btu gas (such as natural gas) also may be burned. Typically, energy consumption for this process is about 2.0 million Btu/ton of coke.¹ This does not include the coal itself. As shown in Table 4, during the years prior to 1971, coal consumption remained fairly constant, but in 1971 there was a sharp drop.

Table 4. HISTORICAL COAL CONSUMPTION FOR
THE IRON AND STEEL INDUSTRY²

<u>Year</u>	<u>Coke</u>	<u>Steam</u>	<u>Other</u>
	<u>10¹² Btu</u>		
1962	1729.2	169.2	14.0
1963	1779.8	162.1	18.3
1964	2062.0	165.8	18.7
1965	2199.1	175.2	17.9
1966	2240.8	173.8	19.9
1967	2166.8	159.8	20.5
1968	2128.8	160.0	17.5
1969	2202.6	140.5	13.9
1970	2285.0	124.5	8.3
1971	1960.4	114.2	7.1

This drop presumably is due to the reduction in steel production during that year. Coke consumption and hence coal usage are expected to decrease on a unit-of-production basis, but total coke consumption is expected to increase with increases in steel production. Based on a 1985 projection for annual pig iron production of 130 million tons, coke

consumption will be about 81 million tons based on a current coke rate of 0.625 ton of coke/ton of iron² produced. Energy consumed for external heat in the production of this amount of coke (neglecting the coal) will be 160 trillion Btu.

Steelmaking Processes

The three basic steelmaking processes in use in the U.S. today are 1) the open-hearth process, 2) the basic oxygen process, and 3) the electric-arc process. In all these processes, molten pig iron, steel scrap, and fluxes are charged into the steelmaking furnace, where they are heated to about 2950°F. Controlled amounts of oxygen are supplied to the molten metal undergoing refining to form oxides with the impurities, which, in turn, either leave the bath as gaseous metallic oxides or form a slag. Composition of the slag is important in steelmaking; consequently, the energy involved in producing the slag also is considered to be a requirement of the steelmaking process. In addition, sufficient heat must be supplied to melt the scrap and superheat the molten bath to the final desired temperature. After completion of the steelmaking process, the molten metal is tapped from the furnace and either transferred directly to continuous casting machines or formed into ingots for use later in rolling mills, bloom mills, slabbing mills, and billet mills.

The Open-Hearth Steelmaking Process

The open-hearth furnace is essentially a regenerative, reverberatory furnace in which a long, relatively shallow bath is heated by radiation from a luminous flame. Burners and air ports are located on both sides of the furnace. Fuel is fed into the furnace through burners on one side of the furnace. Air for combustion is fed into the furnace through regenerators, where it is preheated. After combustion is completed, the flue products leave the furnace through the air port temporarily not in use for entrance of fuel and air and pass through the checkers in the regenerators, heating them as they leave. After 15 or 20 minutes, the fuel is shut off and the air flow reversed; the port previously used for an exit becomes an entrance, and the entrance becomes the exit port. The fuel then is turned on again, and this time it is introduced on the opposite side of the furnace from which it started. These reversals, as they are called, occur every 15 or 20 minutes until the desired product is reached and tapped from the furnace.

For the last 50 years, the open-hearth furnace has been the workhorse of the steel industry, accounting for 90% of the total steel produced. However, after 1960, the amount of steel produced by the open hearths declined in favor of the basic oxygen furnace (BOF) and the electric furnace (Figure 7).

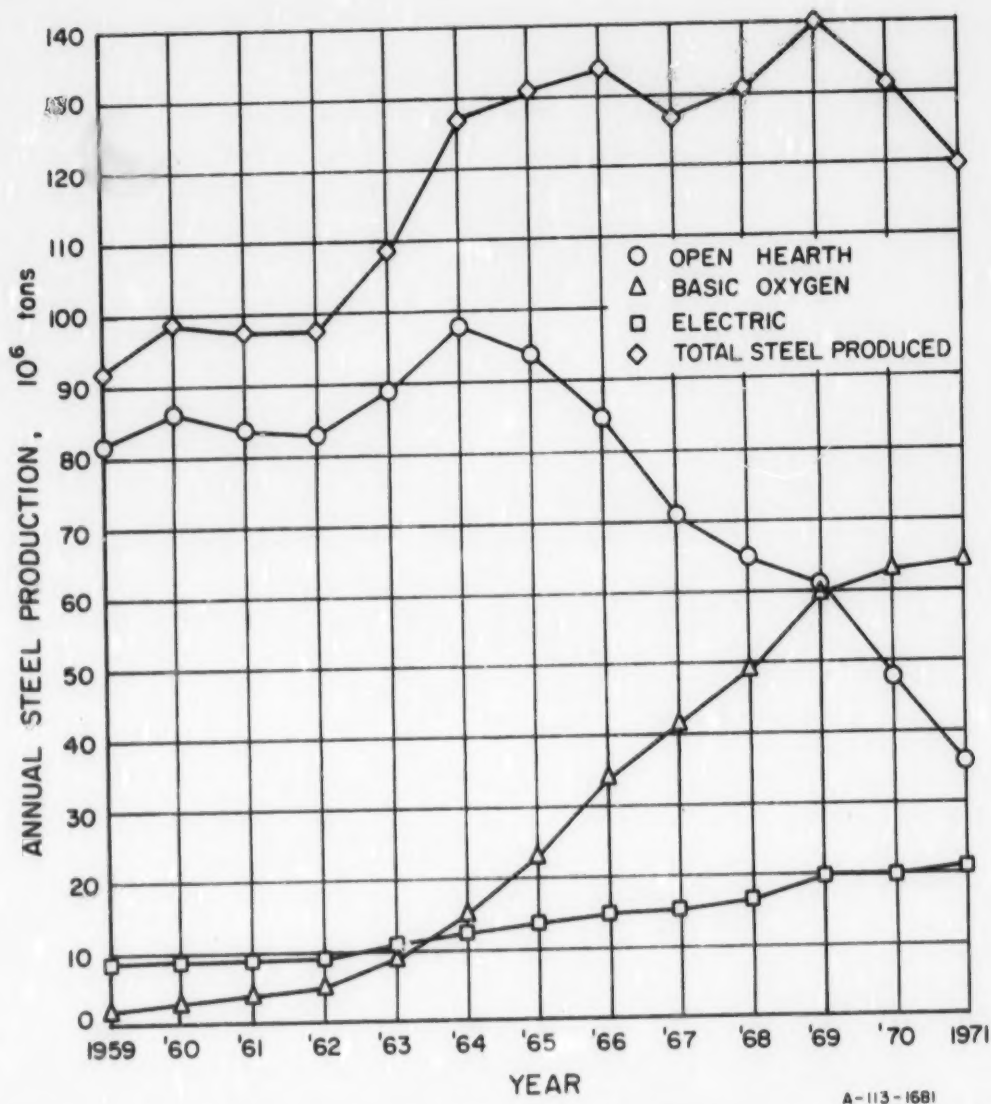


Figure 7. PRODUCTION OF STEEL BY THE OPEN-HEARTH, BOF, AND ELECTRIC-ARC PROCESSES BETWEEN 1959 AND 1971

Today, the open-hearth process produces less than 30% of the annual total steel production. As would be expected, energy consumption by open hearths has decreased proportionally. Energy consumption per ton of steel by open hearths also has decreased because of improvements in furnaces. In 1960, open hearths consumed approximately 4.0 million Btu of energy per ton of steel produced. By 1971, energy consumption had decreased to approximately 3.5 million Btu/ton of steel produced.

In 1960, open-hearth furnaces consumed a total of 344 trillion Btu of energy. By 1971, the total energy consumption by open hearths declined to 122 trillion Btu. The fuels used in open-hearth steelmaking furnaces are of two types, usually called internal and external. The internal fuels are the elements in the melt that are oxidizable. These elements are introduced primarily by the hot metal portion of the charge. The external fuels are the fuels, gaseous and liquid, that are burned in the space over the charge and bath.

External fuels used in the open-hearth furnace process depend on required flame characteristics for the production rate desired and economics. Open hearths can be fired with 100% liquid fuels or with liquid-gas fuel combinations because gaseous fuel flames do not have the necessary luminosity when used alone. Thus, they normally are burned with the addition of liquid fuels to develop luminosity and increase heat transfer to the bath. The following discussion of the fuels presents other factors that relate to their selection in this process.

The primary factors affecting the use of natural gas in open hearths are its availability and cost. Although natural gas is not used by itself, it is used to atomize liquid fuels, thus resulting in a shorter, more luminous, hotter flame that increases heat transfer and productivity. Natural gas is an ideal fuel from metallurgical and air pollution standpoints because it contains virtually no sulfur. When natural gas is available and economically justified, it is usually fired with about 20% liquid fuel to increase its luminosity. Finally, natural gas can be used in gas-oxygen burners mounted in the furnace roof to assist in the heating of scrap.

Some furnaces burn only fuel oil. Fuel oil combustion produces a highly luminous flame that has the required high heat transfer rate to the charge. Heavy fuel oils must be heated to lower the viscosity and then are atomized with natural gas, steam, or compressed air. Fuel oils with 1% or less sulfur content must be used in this application. Of all the possible liquid and gaseous fuel combinations, fuel oil plus natural gas is the most popular.

Tar and pitch flames offer the same general characteristics as fuel oil. One difference is that tar and pitch flames are more luminous, but they are more difficult to burn in a controlled manner. However, more coke tar and pitch are being used in this application because of the decrease in sales demand for this coke-oven by-product. In some cases, coke-oven pitch is blended with about 25% petroleum tar to lower the viscosity of the pitch.

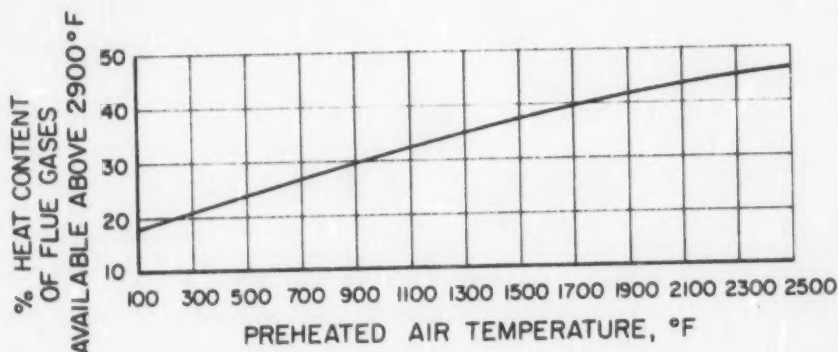
Coke-oven gas is used most often with liquid fuels or natural gas and liquid fuels. However, the maintenance problems with coke-oven gas are significantly greater than those with natural gas because of the presence of trace amounts of corrosive materials in the gas.

Factors Affecting Energy Consumption in Open-Hearth Furnaces

Three primary factors affect the energy consumption of open-hearth furnaces: 1) the percentage of scrap steel charged into the furnace, 2) the combustion air preheat temperature, and 3) the oxygen used to enrich the combustion air, used to increase the oxidation reactions by injection through the slag into the hot metal, and used in gas-oxygen burners.

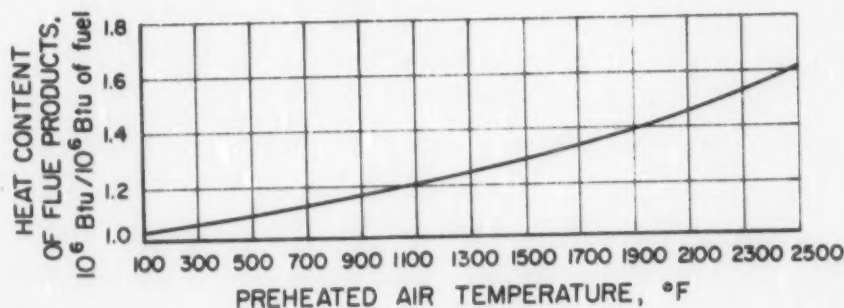
Scrap. The use of scrap in the open-hearth furnace process is primarily one of economics. The economics vary, depending on location of the plant, proximity to adequate raw materials, the amount of molten pig iron available, and the scrap available from integrated units. Energy is required to melt down the scrap; thus, increases in the amount of scrap charged increase the energy consumption. For example, in 1968 the average percentage of scrap charged to open-hearth furnaces increased 3%, from 41% to 44% of the total charge. During this same period, the average energy consumption increased by approximately 8%, from 3.25 to 3.55 million Btu/ton of steel produced.

Preheated Air. The use of preheated air for combustion reduces the energy consumption in an open-hearth furnace by decreasing the amount of heat required to raise the air temperature up to furnace temperature. With increases in preheat air temperatures, the heat content of the combustion products increases and likewise the available heat increases (Figures 8 and 9).¹³



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Figure 8. EFFECT OF PREHEATING COMBUSTION AIR ON HEAT AVAILABILITY



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Figure 9. EFFECT OF PREHEATING COMBUSTION AIR ON HEAT CONTENT OF FLUE PRODUCTS

Oxygen. The most significant effect of the use of oxygen in open-hearth furnaces is that from the injection of the oxygen through the slag layer into the molten metal. Prior to oxygen injection, oxygen from the air would diffuse through the slag layer covering the melt, causing decarburization by oxidation, an exothermic reaction. The speed of decarburization (about 0.005% carbon per minute) was limited by the diffusion rate. By injecting the oxygen through the slag, this limitation

was lifted and refining times were reduced drastically. With oxygen, productivity increases, steel quality improves, and energy consumption decreases.⁷

The amount of the reduction of energy consumption by using oxygen injection depends, to a large extent, on the percentage of hot metal charged into the furnace because of the "internal" fuel and sensible heat contained in the hot metal. Typically, fuel consumption per ton of steel can be reduced by 25-50% over a range of 30-60% hot metal in the charge.

The use of oxygen-enriched combustion air and gas-oxygen burners generally increases flame temperature and available heat, thus improving the melting rate. Of these two methods, gas-oxygen burners are more popular. However, both methods increase productivity and decrease energy consumption per ton of steel produced. Both methods also are used when a reduction in flue products volume is required because of regenerator capacities.

Other Factors. Several other factors in open-hearth furnaces can affect the economy of the operation, especially fuel consumption. Most of these factors relate to furnace design and maintenance, proper flame control, charge composition, type and grade of steel produced, and types of fuel and air controls and instrumentation. The importance of these factors is not dealt with here, as reason alone dictates the overall resultant effects if these factors are ignored.

There are other uses of energy in open-hearth furnace processes, primarily electricity for mechanical drives. A significant amount of electricity also is used in the production of oxygen. These energy uses are discussed in a later section.

The Basic Oxygen Furnace (BOF) Process

In the BOF steelmaking process, pure oxygen is injected through water-cooled lances at high velocities into a bath of molten metal from the blast furnace contained in an upright open-top vessel. A large amount of heat is generated by the oxidation of carbon, silicon, manganese, phosphorus, and iron in the hot metal, and violent agitation of the bath occurs. The amount of heat generated by these reactions is generally more than is required, so scrap usually is added to the charge to absorb the excess

heat and lower the operating temperature. Virtually no auxiliary fuel is required in the BOF process; all the necessary heat is supplied by the fuel value of certain elements in the hot metal.¹⁶

During the past 15 years, the BOF process has experienced a significant growth in usage. Figure 7 shows that from 1959 to 1971, BOF production increased from less than 5% to more than 50% of the total annual steel production in the U.S.² This growth is expected to continue as more open-hearth furnaces are phased out of operation and as the demand for steel increases.

Several reasons for the popularity of the BOF process exist. First is the high speed of operation. Typically, the time required to complete a cycle, or heat, is 30-40 minutes, and as a result, production capabilities are high. Second, no auxiliary fuel is required for operation. However, small amounts of fuel (about 200,000 Btu/ton of steel) are used to maintain the furnace temperature between heats and to dry and 'burn in' new refractory linings.

Oxygen Utilization in the BOF and Energy Requirements for Production

The amount of oxygen used per ton of steel produced in a BOF depends on several factors:

1. The composition of the cold charge if cold pig iron and cast iron scrap are charged together with steel scrap
2. The percentage of hot metal in the charge
3. The composition of the hot metal
4. The required carbon content in the steel at the end of the heat
5. The degree to which the process is under control in terms of iron oxidation and other factors.

The average historical consumption of oxygen per ton of BOF steel produced annually is presented in Figure 10. These data show that oxygen consumption is slowly decreasing; it should continue to decrease as more experience is obtained and better process control achieved.

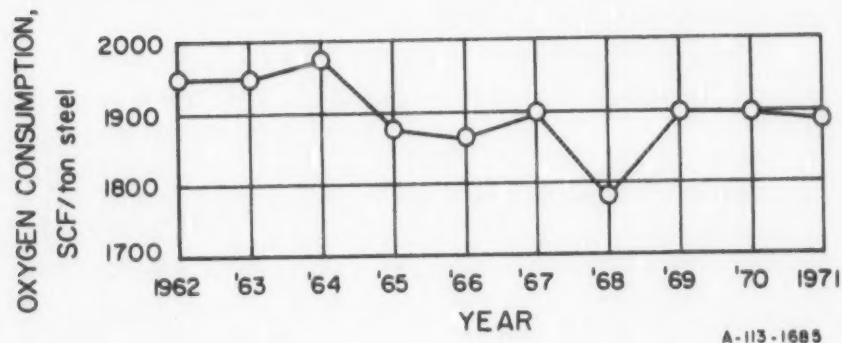


Figure 10. AVERAGE OXYGEN CONSUMPTION BY BOF's

At present, the most economical way to produce large volumes of high-purity (99.5% O_2) oxygen is by liquefaction of air in a compression cooling-expansion cycle, followed by fractional distillation of the liquid air to obtain gaseous oxygen. The production of oxygen in a large plant requires approximately 280 kWhr of electricity per ton of oxygen produced at atmospheric pressure. To this figure must be added the energy required (60 kWhr/ton) to compress the oxygen to steel plant requirements, about 250 psig. If the final product is to be liquid oxygen, the total energy required will be about 750 kWhr/ton of oxygen. Assuming the use of gaseous oxygen at an average rate of 1900 SCF of oxygen per ton of BOF steel, approximately 26.0 kWhr, or 90,000 Btu, of electricity are consumed to produce the required oxygen. For those situations in which storage of the oxygen is desired, the energy consumption increases by nearly 100%.

Note that most steel companies purchase their oxygen from vendors who pipe the oxygen to the steel plant from the oxygen plant. Thus, technically the energy consumed at the oxygen plant to produce the oxygen is not a direct factor in the energy consumption pattern of the steel industry. It is included here because of the importance of oxygen in the steel industry and because it is a substitute for fuels that would otherwise be used.

BOF Efficiency

Based on the theoretical heat available in the BOF process and assuming no waste-heat boilers or carbon monoxide gas collection, the thermal efficiency of a BOF is roughly 65%. Meaningful comparisons with open-hearth processes are not possible because of the different compositions of the charges. Typically, a BOF operates over the range of 70-85% hot metal in the charge, whereas open hearths operate in the 30-65% range. Improvement of the efficiency of the BOF process can be achieved by proper heat recovery treatment of the off-gases and subsequent use of this heat in boilers. The overall effect, while possibly increasing the efficiency to perhaps 75%, would be relatively small, on the order of 150,000-250,000 Btu/ton of steel produced.²²

A significant amount of work is being done to increase the scrap utilization percentage of BOF's. This includes the preheating of the scrap external to the BOF. Serious technical and engineering problems still exist, but should such a process become feasible, energy consumption would decrease because of the increased productivity that would result from a shortened oxygen-refining cycle.

Electric-Arc Furnaces

The third process for producing steel is by means of an electric steelmaking furnace. In this process, scrap iron and steel are melted and superheated to the refining temperature by using three-phase electric-arc power and graphite electrodes. Note that the electric steelmaking process is not competitive with either the open-hearth or the BOF process in integrated steel mills where molten pig iron is available. But electric-arc furnaces are used in "cold-charge" nonintegrated steel plants when additional melting capacity is required.

During the meltdown of the scrap charge, oxidation reactions begin when a pool of molten metal is formed by using oxygen from rust and scale in the charge and from the air. Iron ore also is used as a source of oxygen if it is charged with the scrap. The refining stage is an intensified oxidation period during which carbon, manganese, phosphorous, iron, and aluminum are oxidized.^{4,5}

Electric-arc production of steel has been in use in the U.S. since 1906. Since then, steel production in electric-arc furnaces has grown at a slow but continuous pace, with rapid expansion beginning after World War II. The annual production of more than 20 million tons in 1971 is more than 3 times the annual production in 1948.² Still it represents only a small portion of the total steel production in the U.S.

The major advantage of the electric-arc furnace over the other steel-making processes is its universal applicability as a melting device in which the entire spectrum of modern steelmaking can be controlled independently of the charge materials. The major drawback to this process is centered around economics, which are not truly competitive as yet with other steelmaking processes.

Energy used in this process is primarily electrical; electric discharges or arcs between graphite electrodes produce extremely high local temperatures for melting of the metal. Other heat inputs include heat from slow oxidation of the electrodes, radiant heat from the resistance-heated electrodes, and exothermic reaction if oxygen is injected.

Typically an electric-arc furnace consumes about 500 kWhr of electricity per ton of steel produced. Thus, in 1971, 10 billion kWhr, or 35 trillion Btu, of energy was consumed by electric-arc furnaces.*

Effect of Product Type

The electric steelmaking process produces three types of steel: carbon, alloy, and stainless steels. Figures on total electric consumption by electric-arc furnaces and by type of steel are not available. Estimates of energy consumption by type of steel produced are that carbon steels require an average of 490 kWhr/ton of steel produced and alloy and stainless steels require about 540 kWhr/ton of steel. Thus, the production of alloy and stainless steels requires about 10% more electricity than that of carbon steels.

Power Input

In electric steelmaking, two measures of efficiency exist: 1) the amount of steel produced per hour from a furnace as compared with

* Excludes energy consumed for electricity generation.

that from other furnaces of the same size, and 2) the electricity consumed per ton of steel produced. Energy input rate and heat time affect both of these measurements. However, power inputs do not increase proportionally to the increases in furnace volume. Consequently, ultrahigh power, 300-450 kW/ton of capacity, furnaces are becoming more widely used.²³ The advantages of ultrahigh power furnaces are -

- Decrease in melting time, compared with that in conventional furnaces (120-190 kW/ton of capacity)
- Increased productivity
- Decrease in energy requirements (kWhr/ton of steel)
- Decrease in electrode costs.

No decreases in refining time can be achieved by using ultrahigh power in furnaces. In addition, the unit cost of electric energy in terms of demand charges increases, unless steps are taken to prevent such an occurrence by minimizing the low-power and off-power periods. As long as productivity is increased with increased power, this process is economical.

Scrap Preheating

The reasons for preheating the scrap charged to an electric furnace are obvious. Temperature is directly related to the rate at which heat can be transferred to a load. Considering that electricity is more expensive than fossil fuels, economics dictate that the scrap should be preheated by using cheaper fossil fuels prior to charging and that the electricity then be used for melting and superheating the steel to the required temperature.

Work on scrap preheating indicates that significant decreases in electric energy and subsequently in electric consumption can be achieved. Preheating the scrap to 930°F with a base energy usage of 555 kWhr/ton resulted in an 18% decrease in electric energy consumption, a 19.8% increase in productivity, and a 23.9% decrease in electrode consumption. Indications are that increasing the preheat temperature to 1800°F would reduce the electric energy consumption by 45%. Even so, energy then will be required to preheat the scrap, and the total net decrease in energy consumption will be somewhat less.²⁰

Although scrap preheating has numerous advantages, several technical problems exist; consequently, the practice is in very limited use. The problems involve control of air pollution, control of oxidation of the scrap, and handling of the material. Furthermore, the economics of the process depend, to a large extent, on the cost of the scrap, which generally is quite high. Under these circumstances, the use of prereduced iron ore becomes attractive.

Prereduced Iron Ore Charges

The use of prereduced iron ore in the electric steelmaking process is increasing because of decreases in scrap availability and increases in scrap prices.¹² Furthermore, in some cases, the use of prereduced ore in an electric furnace is slightly more economical than the conventional blast furnace — BOF or open-hearth — process.

In considering energy consumption by an electric furnace using prereduced ore, the energy requirements for the direct reduction process also must be considered. Comparisons between direct reduction and blast-furnace processes are difficult because the forms of the products are different, the prereduced ore being solid state and at room temperature, whereas the blast-furnace product is molten and at 2900°F. In addition, energy consumption by direct reduction processes depends on which process is used, with a range of 13-20 million Btu/ton of metal produced. A good average consumption figure is 15 million Btu/ton.⁶ In terms of energy consumed by direct reduction, the important fact is that the process does not require the use of coking coals. When carbon is the main reducing agent, it usually is supplied as coal or a low-temperature char made from coal. Some processes use carbon monoxide or hydrogen as reducing agents, but the more common practice is to use both. In this case, natural gas is reformed to produce both carbon monoxide and hydrogen. Apparently, the demand for high-quality metallurgical coking coal will be lower, and the demand for lower grade coals, natural gas, and petroleum will increase.

The use of prereduced ore in an electric-arc furnace results in a slight increase in energy consumption and in melt-in time when charged in a batch operation. However, if a continuous feed system is used for charging the scrap and ore, energy consumption is still higher than if only scrap were charged. Nevertheless, the total time required for the process is decreased and the process becomes more economical. Because of the relative newness of this process, reliable information on energy consumption is not yet available. Experimental work with this process showed that the ideal percentage of prereduced ore charged was 25% (percentages higher than this resulting in a decrease in productivity) and that energy consumption was about 560 kWhr/ton, or about 10% higher than without prereduced ore.

Steel-Finishing Processes

At the end of the steelmaking processes, the molten steel is tapped from the furnace and poured into ingots. The ingots are either stored or sent directly to the soaking pits, where they are heated to sufficient temperature to be formed into slabs, billets, or blooms, which are then transferred to the reheat furnaces. Upon completion of reheating, the steel goes directly to the mills, where it is worked and shaped into the final physical forms. Some of these products then are heat-treated and finished.

Soaking Pit Furnaces

Soaking pits are usually deep, square, or rectangular furnaces that have a retractable cover to permit charging and discharging from the top. A few circular pits are bottom or tangentially fired. The pits are usually built in batteries (side by side with a common wall between them) and thus are capable of sharing common air blowers, air supply ducts, waste-gas ducts, and stacks. Soaking pits are generally characterized by the type of firing system, such as one-way-fired, recuperative pit, top two-way-fired regenerative, bottom two-way-fired, and circular tangentially fired. Fuels used include coke-oven gas, blast-furnace gas, natural gas, and gas mixtures. Residual oil primarily is used as a standby fuel. The heat requirements of soaking pits vary, depending upon the initial temperature of the ingots being heated. For cold ingots, heating requirements are typically 800,000-1,000,000 Btu/ton of raw steel; for ingots at 1700°F, the heat requirement is about 400,000-500,000 Btu/ton of raw steel.

Three main factors influence the heat requirements in soaking pits: 1) the type of steel being produced, 2) the size of the ingots, and 3) the track time, that is, time from finish of pouring of ingot to charging into soaking pit. The operator in the steel mill has no control over the first two factors. The type of steel being processed affects track time. Some steel ingots must be completely solidified before they can be charged, whereas others can be charged with molten cores. The size of the ingots depends upon the product mix of the particular plant. Track time affects the heating requirements simply because the more heat lost before charging, the more heat will be required to bring the ingot back to temperature. Figure 11 shows the effect of ingot-charging temperature and percentage of cold steel charged on net Btu/ton heating to 2400°F.

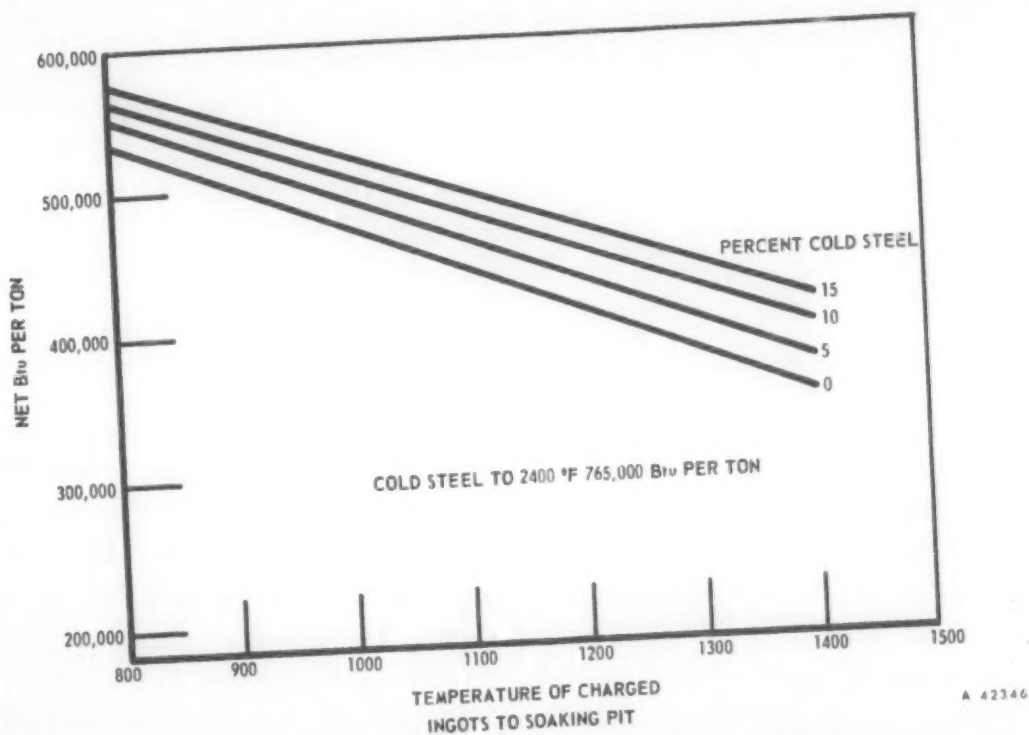


Figure 11. SOAKING PIT. EFFECT OF INGOT-CHARGING TEMPERATURE AND PERCENTAGE OF COLD STEEL CHARGED ON NET Btu/TON HEATING TO 2400°F

Soaking pit efficiencies are generally low, around 50%, primarily because of the sensible heat lost in the flue gases. Preheating of the combustion air by recuperators or regenerators is mandatory if fuel requirements are to be reduced, but these systems are generally not economical.

Continuous Casting and Pressure Pouring

Continuous casting and pressure pouring are two alternatives to ingot pouring that are currently gaining widespread use. In these processes, the molten steel from the steelmaking process is cast into slabs, billets, or blooms, thus eliminating the pouring of ingots altogether. These processes result in significant savings because the need for soaking pits and rolling mills to roll the ingots to slabs is eliminated. Continuous casting consumes a very small amount of energy (200,000-300,000 Btu/ton) and, at the same time, results in a saving of close to 2 million Btu/ton of slab. In addition, the yield of semifinished product is significantly higher with continuous casting than via the ingot route.

Continuous casting was developed in the 1940's. By 1968, about 4.5 million tons of steel was continuously cast, approximately 3% of the total annual steel production. By 1985, it is forecast that 40 million tons of steel will be continuously cast, amounting to 20% of the expected total annual production.

In continuous casting, the molten steel flows from a holding ladle into a tundish, which serves as an intermediate reservoir. From there, it passes into the molds, where it is partially solidified. The strand, as it is called, is cooled to complete solidification; then it is cut into sections by gas torches or hydraulic shears. The energy used is primarily electric energy and natural gas for preheating the tundishes.

Pressure pouring is achieved by exerting air pressure on the surface of the molten steel in an enclosed tank, forcing the molten steel up through a tube into a graphite mold. Unlike continuous casting, which produces a continuous strand that is then cut, pressure pouring produces individual slabs. Energy requirements are about 60,000 Btu/net ton of pressure-poured steel.¹⁸ Electric energy, used primarily for handling of the molds, is estimated to be 5 kWhr/ton of steel cast. The remaining energy

requirement is 42,000 Btu/net ton cast of natural gas for preheating the pressure-pouring tubes. The energy saving by using pressure pouring is nearly 2 million Btu/ton of steel, compared with ingot pouring and later reheating.

In addition to the energy saving due to elimination of the soaking pits, energy savings occur in the melting operation because continuous casting produces a higher yield (95%) than the ingot route (85%). Consequently, less steel is required to meet production demands via the continuous casting route. The difference is about 0.128 net ton of steel. By assuming an electric furnace for steel production rated at 525 kWhr/net ton, the energy saving would be 64.6 kWhr (0.123×525), or 220,415 Btu/net ton of semifinished product.

Reheat Furnaces

Reheat furnaces, as discussed here, are those furnaces used for heating the semifinished steel products in preparation for the final hot-rolling operations. Reheat furnaces can be either continuous or batch type, but most steel plants use continuous furnaces. Continuous furnaces fall into two categories: pusher and conveyor furnaces. Walking beam and roller hearth furnaces are two types of conveyor furnaces typically used. Fuels used in reheat furnaces are fuel oil, coke-oven gas, and natural gas; the last has become the predominant fuel in recent years. Fuel consumption by reheat furnaces ranges from about 1.6 to 3.0 million Btu/net ton of steel. In 1971, reheating the billets, blooms, and slabs consumed approximately 191 trillion Btu of energy.

The primary factors that affect the heat requirements for reheating furnaces are 1) the type of furnace (batch or continuous), 2) the size of the furnace, 3) the furnace design, 4) the temperature of the process, and 5) the physical nature of the steel being reheated. For example, the average fuel consumption for slab-reheating furnaces that burn oil or gas fuels with preheated air is about 2.2 million Btu/ton heated for three-zone furnaces and 2.8 million for higher capacity five-zone furnaces. Thicker slabs require longer heating times and more energy. Fuel economy for steel mill reheat furnaces also is affected by heat losses, heat recovery, combustion and process controls, and operating practices. Frequent rolling mill delays adversely affect fuel efficiency and temperature

uniformity of the product. Because of the large number of factors that can affect fuel economy in reheat furnaces, for which specific information is not available, a detailed fuel utilization analysis is not possible.

Effect of New Technology on Energy Consumption

Currently, four developments in technology are expected to have a significant effect on the energy consumption of the ironmaking process:

1) the use of prereduced iron as part of the blast burden, 2) use of formcoke, 3) injection of reformed gas, and 4) the use of nuclear reactors. The effects of each of these are examined later in this section in several hypothetical cases.

The single most important change in energy consumption in steelmaking in the future will be the phasing out of open-hearth furnaces in favor of BOF's and electric-arc furnaces. On the basis of production statistics,² 124 trillion Btu of energy was consumed by this process in 1971. Energy consumed by BOF's amounted to about 95 trillion Btu; 90% of this energy is accounted for by the exothermic reactions of the process and the sensible heat of the final product, and the remaining 10% is consumed in the production of oxygen. Electric-arc furnaces consumed about 35.6 trillion Btu of energy. Phasing out of the open-hearth furnaces would result in a 4% reduction in energy consumption by the industry, assuming the BOF's produce the bulk of the steel.

Most of the "new" technology available for use on reheating furnaces for both semifinished or final hot-rolled products includes such items as improved burners for more uniform heating, improved combustion controls such as programmed burner operation, oxygen enrichment of combustion, improved skid rails, and improved monitoring devices. In such cases, the effect of these technologies on the fuel utilization of reheating furnaces cannot be determined. The only new developments that have shown an ability to reduce fuel consumption are continuous casting and pressure pouring, which have already been discussed.

The continued use of soaking pits by the steel industry is directly tied to the continued use of slabbing and blooming mills. Thus, the degree to which continuous casting is used (making absolute the slabbing and blooming mills) is important. Several factors are involved. Continuous casting is most suited for steel mills in which the product range is narrow.

Flexibility, product size, and quality limitations will slow down broad application of this process. During the past few years, new soaking pits and rolling mills have been built, indicating a reluctance on the part of the steel industry to accept continuous casting. The large-tonnage continuous-casting installations that have been built are for new capacity, not replacement for existing capacity, so that the traditional type of equipment can act as a backup and can supply a wider range of products than continuous casting. Therefore, under present conditions the use of soaking pits is not expected to decline and may even increase if the increase in steel demand is greater than the increase in continuous casting. By 1985, steel production is expected to be 200 million tons, 20% of it processed through continuous casting.

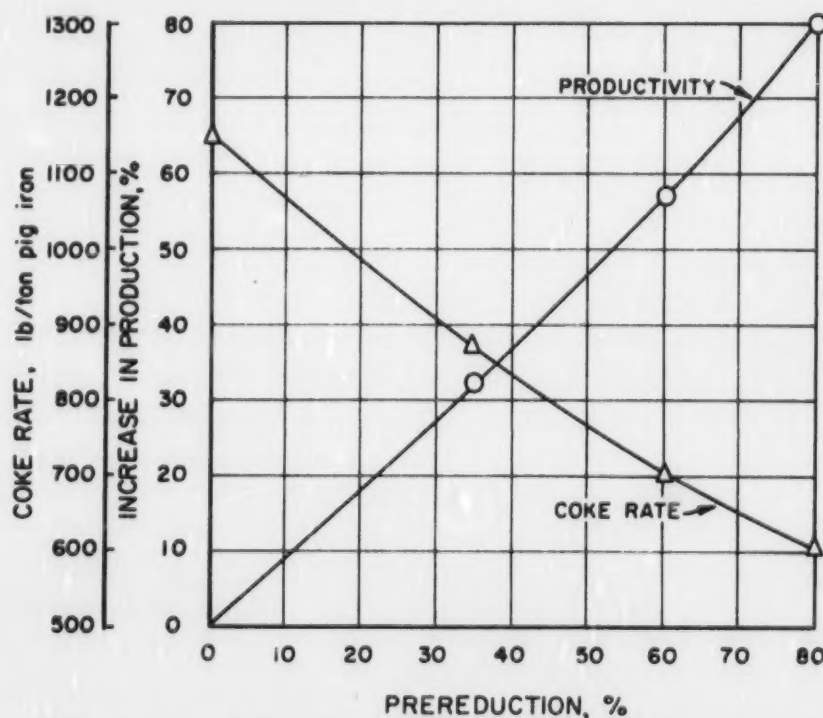
Fuel-fired furnaces for reheating slabs, blooms, and billets are not likely to change in the foreseeable future, partly because of the high capital investment in existing equipment. Furthermore, with the ability to change fuels, a plant can take advantage of changes in cost and availability of different forms of energy. There is no new technology nor are there other factors that are expected to affect fuel usage in reheating furnaces. The long-range goal of the industry is to combine into one step the continuous casting, the temperature equalization in a continuous soaking furnace, and the rolling operations. However, such a process is still a long way off.

Direct Reduction (Prereduced Iron Ore)

Direct reduction is a process in which iron ore is converted directly to steel, thus bypassing the blast-furnace process altogether.¹⁶ Development of a viable direct reduction process has been under investigation for many years, but to date, no one has achieved total success. The result has been the development of a myriad of proposals. Although processes that are referred to as direct reduction do not produce steel from iron ore, they do produce a material of which 85% of the contained iron is in the metallic state. These materials are known variously as reduced pellets, sponge iron, and metallized ore, or, for that matter, prereduced ore. Among the several end uses of this material in the

steel plant are blast-furnace burden and electric-steelmaking-furnace charge. For the present, only usage as a blast-furnace burden is discussed. (A complete discussion of direct reduction is presented later.)

Several trials with prereduced iron ore have been conducted on experimental and industrial blast furnaces within recent years.^{3,17,19-21,30} The results have indicated that substantial increases in production rates can be achieved and, at the same time, coke rates can be reduced. Figure 12 shows that, as the percentage of prereduced ore in the burden increases to 80%, production increases by 70%, or about 9.0% per 10% metallic iron in the burden. This same figure also shows that for the same percentages of prereduced ore, coke rates decrease by about 40%, or 8.2% per 10% metallic iron in the burden. Apparently, as in other methods of reducing coke rates, the amount of available energy in a steel plant produced as off-gas is reduced and consequently must be replaced with purchased fuels. However, the use of prereduced ore in the blast furnace does increase the caloric value of the off-gas, in some cases as much as 30% with an 80% metallized charge.



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Figure 12. EFFECT OF PREREDUCTION ON COKE RATE AND BLAST-FURNACE PRODUCTIVITY

Formcoke

Formcoke is an agglomerate, or briquette, prepared from bituminous coals that do not meet the restrictive specifications of metallurgical coking coals.³¹ The primary advantage of formcoke is that it would replace the coke currently used, which is manufactured from metallurgical coking coals that are in short supply. Although several trials have been conducted, no successful process using formcoke has been developed. Interest is high, however, because successful use of formcoke would result in a lower cost for producing coke and, consequently, a saving in fuel costs. Furthermore, use of formcoke would not upset the energy values recoverable from the formcoke plant because the Btu value and gas volume produced by some of the formcoking operations are equivalent to those obtainable from conventional coke ovens. However, if formcoke becomes a successful substitute for coke in the blast furnace, the possibility exists that additional energy would be required to meet the overall plant requirements, depending on the volume and heating value of the top gas. These questions remain to be answered.

Reformed-Gas Injection

Reformed gas is a low-thermal-value gas that is made by the pyrolysis and steam decomposition of a high-thermal-value fuel. Theoretical studies have indicated that injection of 260 lb (per net ton pig iron) of reformed gas produced from fuel oil into the blast furnace, above the melting zone but below the preparation zone, should result in a 38% increase in production and a 28% decrease in coke rate. Investigations on an experimental facility by the U.S. Bureau of Mines showed that production could be increased by 40% and coke rates decreased by 29% by using 325 lb (per ton of pig iron) of reformed gas injected into the furnace.¹⁸ At present, no commercial process for reformed-gas injection exists, but work is continuing.

Nuclear Energy

Nuclear energy will be used in the steel industry to supply electric energy when nuclear energy costs become competitive with costs of other forms of electricity generation. Methods that have been proposed would utilize nuclear reactors directly in combination with blast furnaces. One

proposed process would utilize gas-cooled nuclear reactors to preheat the reducing gases to 2700°F prior to injection into the furnace. However, such processes are still far in the future.

Air Pollution Emissions Background Information^{11,19,24,29}

A significant factor in the future of the U.S. steel industry will be its ability to solve the air pollution problems created by the various iron- and steelmaking processes. Table 5 summarizes the air pollution emissions from the various ironmaking processes. Emissions from the coke ovens are considered to be the most serious problem facing the steel industry. Of the two processes available for coking, the beehive process produces excessive emissions, which are virtually uncontrollable because of the equipment used in this process. The only means of control, therefore, is a restriction on the location of such ovens near built-up communities. However, because beehive coke ovens are virtually extinct in the U.S., they are of no real concern.

Air Pollution Emissions in Ironmaking

Coke-Oven Emissions

Emissions around a by-product coke-oven plant originate primarily from four operations: 1) charging the coal into the ovens, 2) leakage during carbonization, 3) pushing the coke out of the ovens, and 4) quenching the hot coke with water.

Charging

Charging of the pulverized coal into the coke oven occurs shortly after the oven has been emptied at the end of a coking cycle. Consequently, the oven interior is still at red-hot temperatures. As the charging begins, volatilization of the gases starts immediately, resulting in the release to the atmosphere of visible clouds of yellow-brown smoke. Several improved design features have been developed to reduce the amount of emissions. These modifications include facilities for aspirating the gases from the oven interior during charging, improved charging hole spacing, facilities for enclosing the space between the lorry case (from which the coal is charged) and the coke oven, and various mechanical feed systems that increase the charging rate, thereby decreasing the total amount of escaping smoke. However, these design features usually cannot

Table 5. AIR POLLUTION FROM METALLURGICAL COKING OPERATION
(Unit/Unit Weight of Coal Charged) AND OTHER IRONMAKING PROCESSES

Type of Operation	Particulates, lb/ton	SO _x ' lb/ton	CO, lb/ton	C H _x ' lb/ton	NO _x ' lb/ton	NH ₃ , lb/ton
1. By-product coking						
Unloading	0.4	--	--	--	--	--
Charging	1.5	0.02	0.6	2.5	0.03	0.02
Coking Cycle	0.1	--	0.6	1.5	0.01	0.06
Discharging	0.6	--	0.07	0.2	--	0.1
Quenching	0.9	--	--	--	--	--
Underfiring	--	10	--	--	--	--
2. Beehive Ovens	200	--	1	8	--	2
3. Iron Ore Sintering						
Windbox	20	--	--	--	--	--
Discharge	22	--	44	--	--	--
4. Blast Furnace						
Ore Charge	110	--	--	--	--	--
Agglomerated Charge	40	--	1400-2100	--	--	--

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be incorporated into a coke oven, except between rebuilds, and the period between rebuilds usually amounts to 20-30 years.

Carbonization

The primary source of emissions during carbonization is leakage around the oven doors. Control of emissions during carbonization takes the form of optimum maintenance during operation.

Coking Discharge

At the end of the coking cycle, the coke is pushed from the oven into the coke-quenching cars. The amount of emissions (smoke) depends on the degree of completion of carbonization. Green coke produces large quantities of smoke, whereas very little smoke is produced if the coke is thoroughly carbonized.

Coke Quenching

In the quenching process, the hot coke is transported to the quenching station, where it is quenched with large quantities of water in a short time. The vast clouds of steam that result entrain small particles of coke. However, the quantity of particulates is small and tends to be deposited in the ground within a short distance of the quenching tower. Consequently, the quenching operation is not considered to be a significant source of emissions. For those particulates that are emitted, lower impingement baffles installed in the coke quench tower can reduce the quantity by 85-90%.

Other Sources

Other factors that affect the quantity of emissions in the coking operation include the amount of fines in the coal used and the sulfur content of the coal used. In general, low-sulfur coals are used, thus maintaining sulfur emissions at a minimum. Yet variations in the sulfur content of the coal will vary the amount of sulfur-bearing compounds emitted.

Sintering and Pelletizing Emissions

Air pollutant emissions from sintering processes consist of dust in the waste gases from the sinter strand and from the discharge end of the cooling chamber. Additional dust is emitted by the grinding and blending operations. In addition to the dust (particulates) emissions, sulfur dioxide

and carbon monoxide gases are emitted. The amount of sulfur dioxide emitted depends upon the sulfur concentration of sulfur-bearing native ores.

Air pollutant emissions from pelletizing processes are similar to those from sintering processes. However, particulate emissions are usually lower (numerical documentation not available) because the ore fed into the heating plant is in the form of "green" pellets. Thus, the amount of fines present is significantly reduced.

Blast-Furnace Emissions

Air pollutant emissions from blast furnaces comprise off-gases from the process. As the blast-furnace gas leaves the top of the furnace, it contains large amounts of particulate matter made up of about 30% iron, 15% carbon, 10% silicon dioxide, and small amounts of aluminum oxide, manganese oxide, calcium oxide, and other materials. The gas also contains large amounts of carbon monoxide, which is used for fuel in other areas of the steel plant. During normal operation, air pollutants are emitted during the charging of the burden to the furnace. However, improvements in handling equipment and charging system design have eased the problem.

Summary of Emission Controls in Ironmaking

Typically, emissions from the ironmaking processes are controlled by conventional means, including scrubbers, electrostatic precipitators, cyclones, baghouses, and settling chambers. Table 3 summarizes the controls used and gives the effect of these controls on emissions where data are available.

Air Pollutant Emissions in Steelmaking

Table 6 summarizes the air pollutant emissions from steel-manufacturing processes. In both the open-hearth process and the electric-arc process, the use of oxygen lances to increase production rate increases particulate emissions by a factor of nearly 2. Particulate emissions from the BOF are even higher. These emissions are primarily due to the violent mixing of the bath that occurs as the oxygen is bubbled through. In open-hearth and electric-arc furnaces where no oxygen lancing is used, particulate emissions (dust and fumes) result from the mechanical and chemical reactions in the molten bath itself, and from the combustion of the fuels.

Table 6. AIR POLLUTANT EMISSIONS
FROM STEELMAKING PROCESSES

Type of Operation	<u>Particulates</u> <u>Carbon Monoxide</u>	
	—lb/ton—	
Open Hearth		
Oxygen Lance	22	--
No Lance	12	--
BOF	46	120-150*
Electric Arc		
Oxygen Lance	11	18
No Lance	7	18

* Represents generated emission. After ignition of gas above furnace, the carbon monoxide drops to 0-3.0 lb/ton of steam produced.

The highest rate of particulate emissions occurs during the first half hour after hot metal addition and during the latter 2 hours of ore boil. During the remaining portions of the cycle (roughly 80%), particulate emissions are relatively low.

As is evident from the previous discussion, even with controls, particulate emissions from steelmaking processes will increase as the open-hearth process is phased out and the BOF assumes the major burden of steel production.

Typical methods for controlling these emissions are electrostatic precipitators (98% efficient), venturi scrubbers (85-98% efficient), and baghouses (99% efficient). Hoods that have been developed for BOF's and electric-arc furnaces catch the gases and channel them through the cleanup systems. At the same time, the waste heat from these gases is recovered for use elsewhere. Costs for gas cleanup systems are high, running from \$1.3 million for electric-arc furnaces to \$5.0 million for BOF's.^{27, 28} However, as steel plants become more modern, thus reducing emissions through greater efficiency and economy in the use of resource inputs, these costs should decrease.

Air Pollutant Emissions From Reheating Operations

Emissions from reheating furnaces are primarily due to the combustion of the fuel being used. Because the industry has turned to using automatic combustion controls and instrumentation, smoke is no longer the problem that it once was. The main pollution problem at present is caused by the presence of sulfur in the fuels used in these processes. In order to lower these emissions, fuels with lower percentages of sulfur are being used. However, this is only a temporary solution because the availability of these fuels is decreasing. In addition to sulfur emissions, carbon monoxide and nitrogen oxides are of concern to the industry. The preferred fuel for controlling these emissions is natural gas. As in the case of operating data, no reliable average emission levels are available for the reheating processes because of the large number of processes in existence.

Effect of New Technology on Emissions

With respect to total emissions from the steelmaking process, as the energy consumed is reduced, specifically, as coke rates decrease, total emissions will decrease. As coke rates decrease, less coke must be manufactured; consequently, fewer particulates will be emitted. Similar conclusions can be reached concerning the blast-furnace operation. Conceivably, if coke production is decreased by 50%, a total pollutant emissions will decrease by a similar amount. In addition to particulate emissions, carbon monoxide levels would be reduced. Note that most of the pollution occurs in the off-gases from the coking process. Because these gases are burned elsewhere in the plant, they usually are cleaned before burning. Thus, as better handling equipment becomes available, emissions, which usually occur because of improper handling of the gases, will decrease. Again, these effects are examined in more detail later in this section.

Energy Utilization Patterns - Projections to 1985

The future energy needs of the iron and steel industry will be based on a complex interaction of steel demand, availability and price of fuels, the amount of reusable energy produced by the iron and steel processes, and the implementation of new technology. The following illustrative analysis of

future energy needs is based first on projections of the further implementation of existing but still rather new technology, the steel industry's own projections of the demand for iron and steel, and changes in processes caused by changes in the availability of raw materials and of fuels and in air pollution regulations. The analysis then considers the possible effects of implementing new technology still in the development state. Later in this section, this projection of future energy need is related to pollution emissions and changes in control technology.

Ironmaking Operations

The annual production of iron ore has been rather constant over the 5-year period between 1966 and 1971, that is, about 90 million tons/yr. However, the steel industry predicts that, by 1985, pig iron production will increase to 150 million tons/yr in order to meet the increasing demand observed between 1971 and 1973. In order to predict the annual production of pig iron for the years between 1971 and 1985, the simple linear relationship shown in Figure 13 was assumed. The linear fit was carried out between a production rate of 150 million tons/yr in 1985 and 90 million tons/yr in 1971, which is the average production between 1966 and 1971. This method tends to deemphasize the large drop in production between 1970 and 1971 caused by a poor economic climate, forcing a general decrease in the demand for steel products.

The projection for ore was based on the historical production of ore, compared with pig iron. All iron ore, regardless of pretreatment method, contains approximately the same amount of iron prior to charging into the blast furnace, and the amount of iron necessary to produce 1 ton of pig iron is constant. Hence, the amount of ore needed to produce 1 ton of pig iron can be assumed constant. We have simply assumed (as does the iron and steel industry) that any ore not containing a minimum standard amount of iron at the time of mining will be treated until that standard iron content is achieved.

Based on this assumption and published data, we determined that about 1.47 tons of ore is required per ton of pig iron produced. Consequently, 221 million tons/yr of ore will be needed in 1985 to produce 150 million tons of pig iron. Again, the production of ore between 1971 and 1985 was assumed linear with the 1971 production, which was assumed to be 152 million tons, or the average from 1966 to 1971.

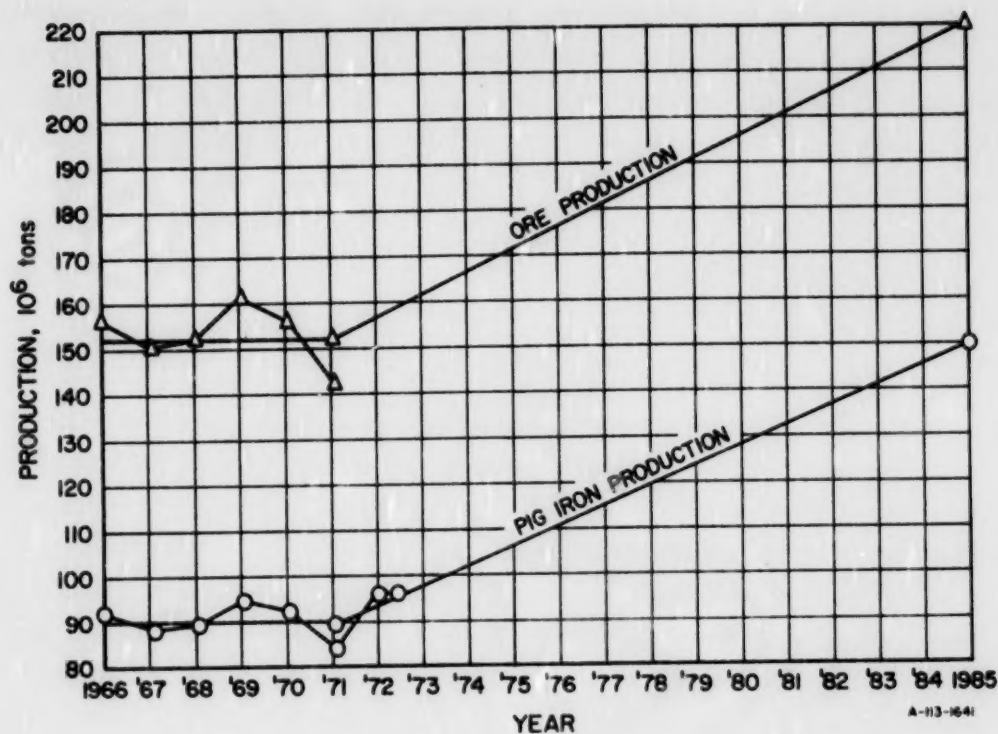


Figure 13. PROJECTED INCREASE OF ORE DEMAND AND PIG IRON PRODUCTION

Iron Ore Preparation

As indicated earlier, iron ore can be mined and charged "as is" into the blast furnace, or it can be pretreated to increase its iron content per ton. The methods of pretreatment are pelletizing or sintering. Pretreated ore has the added advantage of increasing the production of a blast furnace because of the physical structure of the charge or "burden." This has led to a constant rise in the use of pretreatment. However, there is a substantial supply of high-grade ore that will continue to be mined and charged as is. Pretreatment of high-grade ore is economically unsound in spite of some production increases at the blast furnace. Historically, the annual production of crushed ore (untreated) has been maintained at about 40% of total requirements and pretreated ore at about 60% of requirements. What has changed is the ratio of sintered to pelletized

ore. In Figure 14 are plotted the amounts of crushed, sintered, and pelletized ore as percentages of total production.

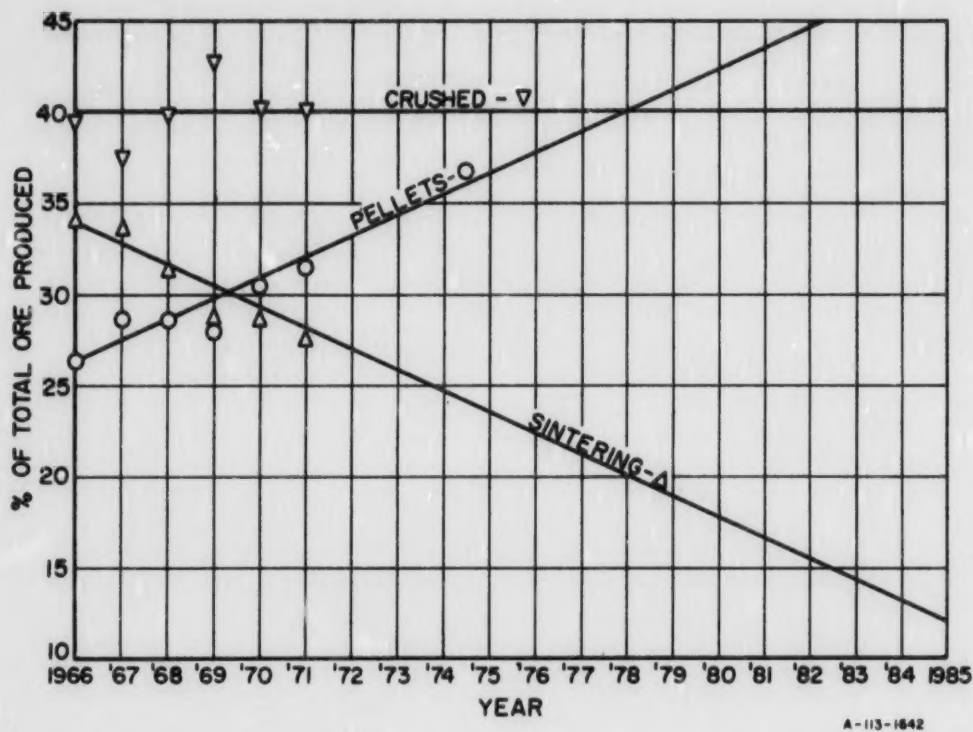
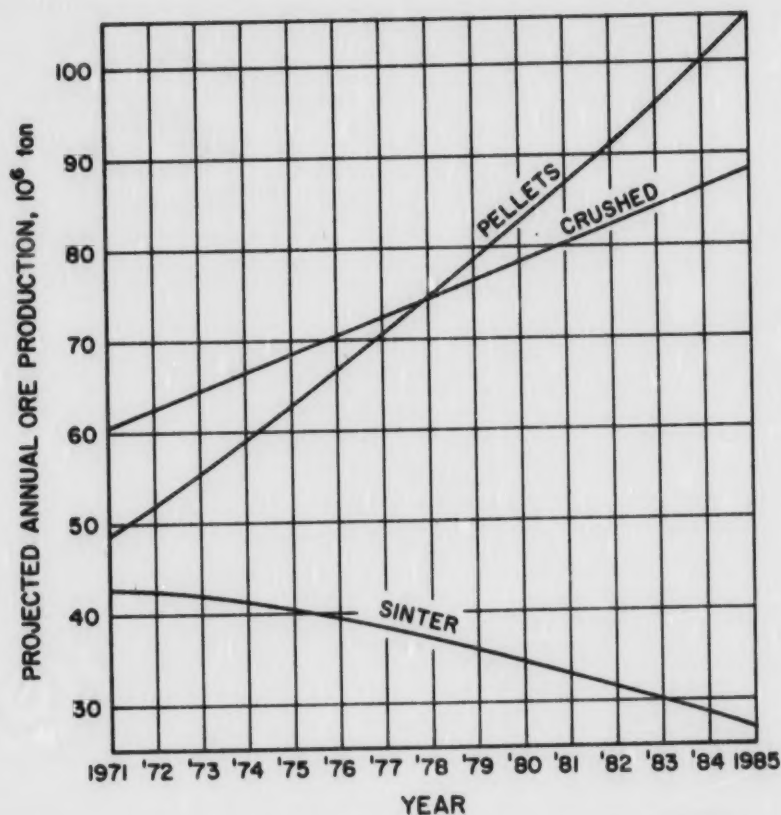


Figure 14. LINEAR PROJECTION OF ORE TREATMENT TRENDS

The trend toward decreasing amounts of sintered ore and increasing amounts of pelletized ore is nearly linear. The projected amounts of sintered and pelletized ore were obtained from a least-squares fit of the production between 1966 and 1971, which was extrapolated to 1985. The total projected production of pretreated ore was found to remain constant at about 60% of the projected total requirements (Figure 14), a finding that substantiates our original assumption of a constant (40%) production of crushed ore.

Based on the projection of sintering, pelletizing, and crushing in terms of percentage of total production and on the projection of total ore requirements, Figure 15 was prepared to show the expected annual production by each ore pretreatment method. After 1978, more ore is expected to be pelletized than produced in any other form. By 1985, the projection indicates that about 33 million tons of ore will be sintered,



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Figure 15. PROJECTED ANNUAL IRON ORE PRODUCTION BY VARIOUS TREATMENT METHODS

89.3 million tons will be used as mined, and 105.2 million tons will be pelletized.

The relative change in the amounts of pelletizing and sintering is important because both the amounts and types of energy required by these processes are significantly different. Pelletizing requires about 600,000 Btu/ton of pellets and uses natural gas or fuel oil exclusively. Coke-oven gas or blast-furnace gas could be used; however, pelletizing is always carried at the mine where these gases are not available. (Pelletizing is carried out at the mine because it is considerably more economical to ship high-grade ore than low-grade untreated ore.) Based on current

energy requirements for pelletizing and the fact that little new technology appears likely to change this energy consumption, total energy consumption was projected to 1985 (Figure 16).

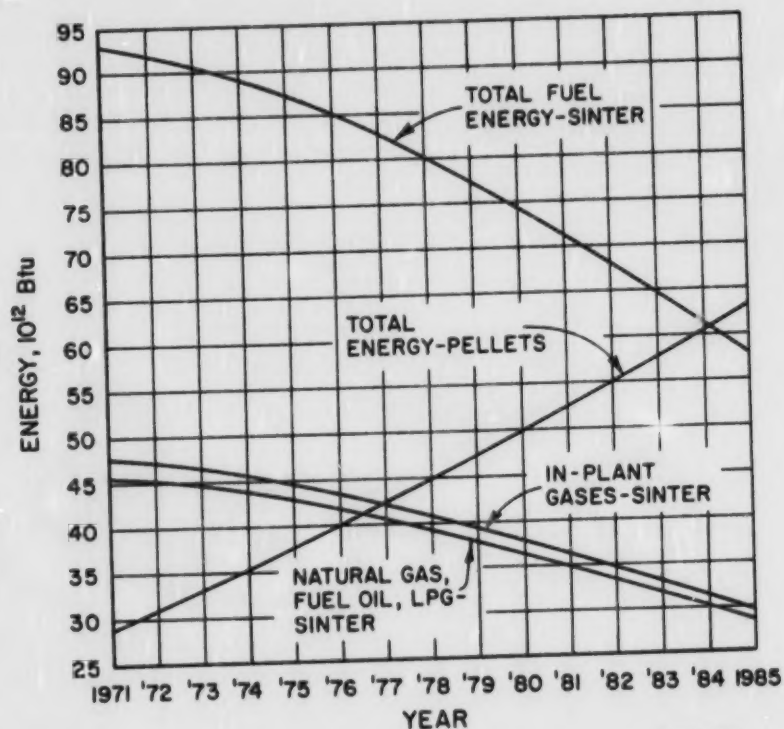


Figure 16. PROJECTED CONSUMPTION OF FUELS FOR IRON ORE SINTERING AND PELLETIZING

Sintering of ore usually is carried out at the steel plant and hence was developed to use either purchased fuels or in-plant gases. (Purchased fuels as used in this report refer to natural gas, fuel oil of all grades, and LPG, but exclude coal.) Sintering requires about 2.2 million Btu/ton of sinter. Historically (1966 to 1971), the amount of purchased fuels about equaled the amount of in-plant gases consumed by this process. More specifically, 51% of the energy used for sintering was in-plant gas and 49% was purchased fuels. Examining the historical split between fuels more closely, we found that it occurred primarily from a need to balance overall plant fuel supply and demand. For this projection, we assumed that the historical split between purchased and in-plant fuels

would continue to 1985. Based on this assumption, the projection of total energy requirements for sintering is shown in Figure 16. Based on a projected decrease in sintering, energy requirements in this area of steelmaking are expected to decrease from 93 trillion Btu/yr in 1971 to 57.5 trillion Btu/yr in 1985.

Coke and Coke-Oven Gas Production

Coke is a major component needed for the production of pig iron in a blast furnace. The amount of coke required by the ironmaking process has decreased steadily in the last 5-10 years because of such things as pretreatment of the ore, higher blast-air temperatures, and better blast-furnace design. The steel industry predicts that coke requirements will continue to decrease from the present level of about 0.63 ton/ton of pig iron to 0.5 ton of coke/ton of pig iron produced in 1985, if hydrocarbon fuels remain available or the research on formcoke use is successful. For this analysis, the decrease was assumed to occur linearly, as shown in Figure 17.

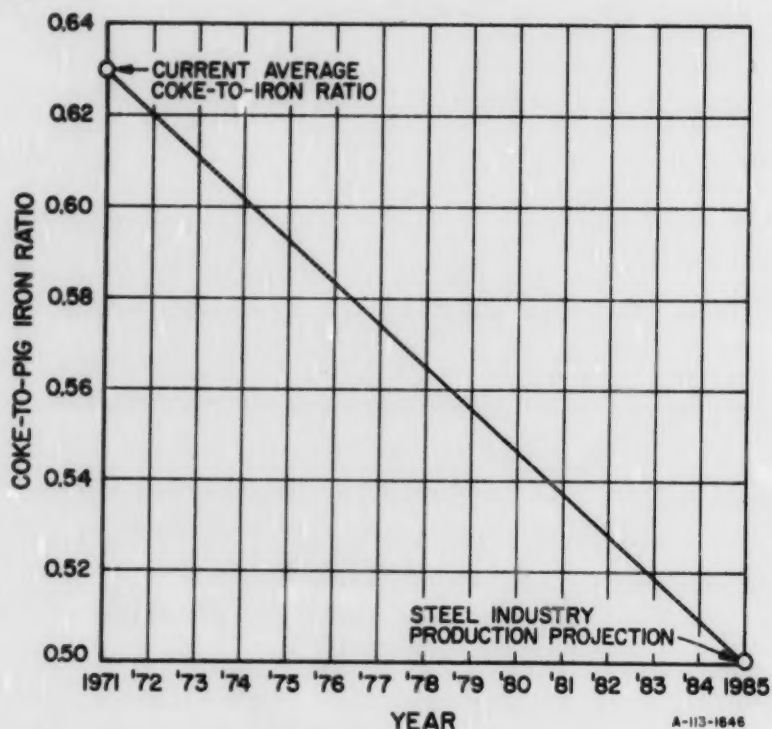


Figure 17. PROJECTION OF DECREASE IN COKE REQUIREMENT PER TON OF PIG IRON PRODUCED

Based on the decreasing demand for coke per ton of pig iron produced and on the predicted increased production of pig iron, the need for coke should increase from the 56 million tons produced in 1971 to only 65 million tons in 1985, as shown in Figure 18.

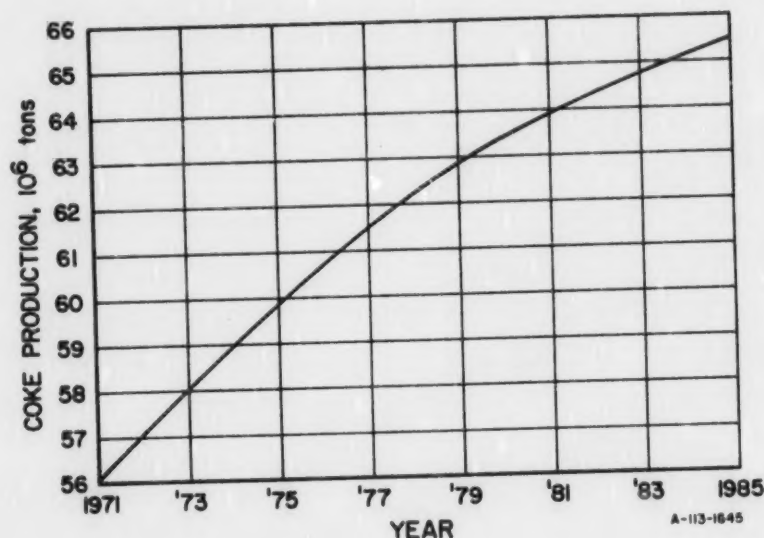


Figure 18. PROJECTION OF REQUIRED COKE PRODUCTION FROM 1970 TO 1985

In the coking operation, about 7 million Btu of coke-oven gas is generated per ton of coke produced. Major changes in coking process hardware are expected to reduce pollutant emissions. However, the heat content per ton of coke of coke-oven gas generated is expected to change very little. Therefore, the fuel available from the coking process in the form of coke-oven gas will increase, along with expected increases in the amount of coke produced. This projected production of coke-oven gas is shown in Figure 19.

Coke is produced in an airtight chamber by distillation of coal brought about by heating the coal. The heat required for this process is supplied by burning almost all (99%+) in-plant gases. About 3.8 million Btu is required for each ton of coke produced. Historically, heat requirements for coking have been fairly constant, so they were assumed to remain constant from now to 1985. Based on this assumption, Figure 20 shows the expected annual consumption of in-plant gases to 1985.

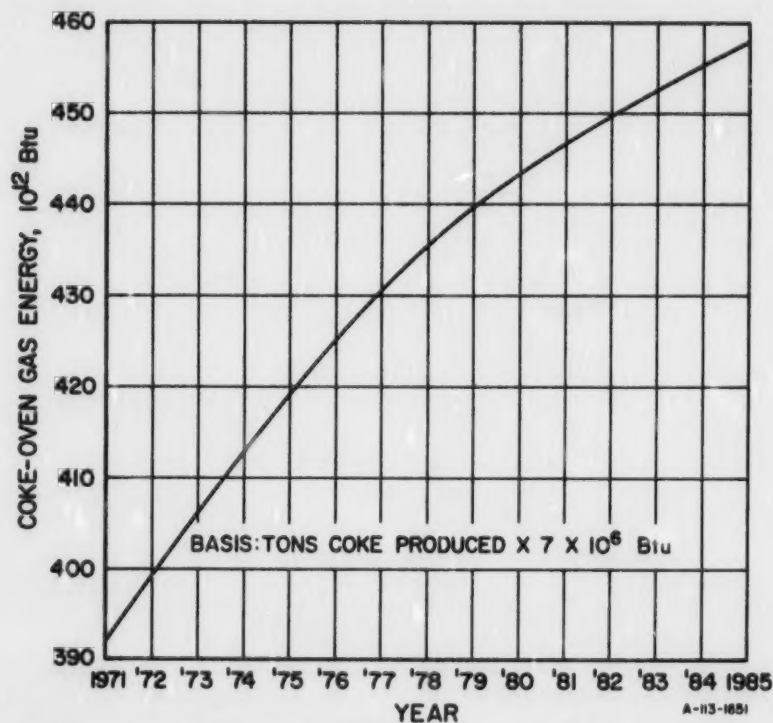


Figure 19. PROJECTED PRODUCTION OF COKE-OVEN-GAS ENERGY BASED ON REQUIRED COKE PRODUCTION

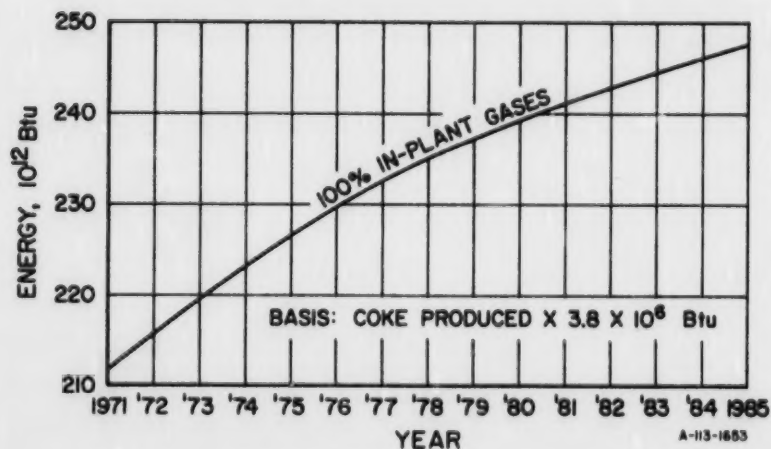


Figure 20. PROJECTED DEMAND FOR IN-PLANT-GAS ENERGY FOR UNDERFIRING COKE OVENS

As a final part of the energy use projection for the coking operation, the coal converted to coke was considered. The amount of coal required to produce 1 ton of coke varies somewhat, depending upon the heating value of the coal used in the process. Therefore, the amount of heat is a more convenient term to use. On this basis, about 36 million Btu of (coal) energy is needed to produce 1 ton of coke. (For a typical coking coal, this is about 1.44 tons.) Figure 21 shows the projected total energy demand for coking coal to the year 1985, as calculated from Figure 18.

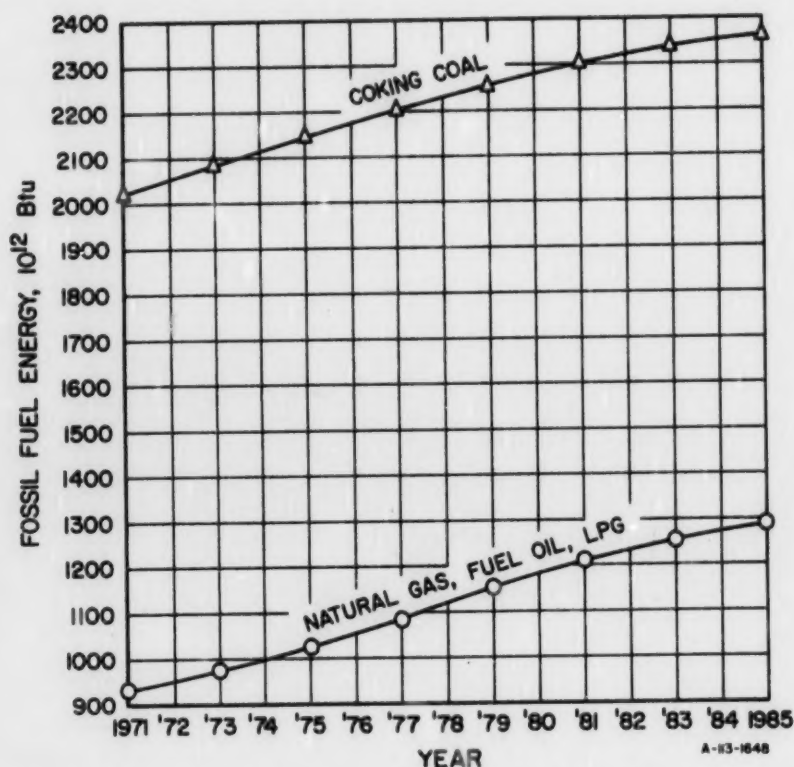


Figure 21. PROJECTION OF TOTAL PURCHASED COKING COAL AND NATURAL GAS, FUEL OIL, AND LPG ENERGY

Blast-Furnace Operation

As described earlier, ore, coke, and fluxes are charged into the blast furnace, which is then heated by injection of hot (blast) air and sometimes hydrocarbon fuels. Two significant historical trends were found in examining this process relative to its energy requirements. First, to increase productivity, the industry was tending to use higher and higher blast-air temperatures and is still increasing the amounts of hydrocarbon fuel injection.

We first obtained data on the amounts of hydrocarbon injection used between 1967 and 1971. We plotted these data in terms of percentage of total iron production and found that the increased usage was nearly linear. We projected this linear growth (Figure 22) to 100% and concluded that all iron would be produced in furnaces using hydrocarbon injection by about 1980.

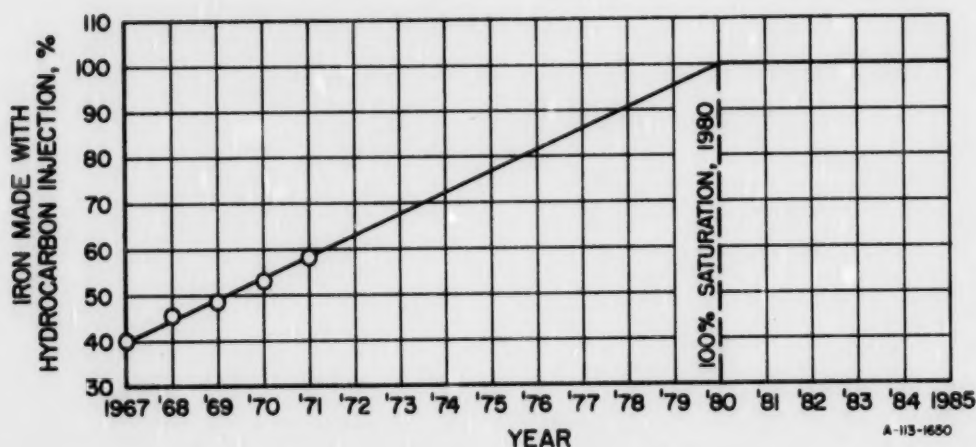


Figure 22. PROJECTION OF PERCENTAGE OF IRON MANUFACTURED BY USING HYDROCARBON INJECTION INTO THE BLAST FURNACES

This method of prediction compares well with an independent steel industry projection that 100% use of hydrocarbon injection would be realized by about 1981.

We then combined the projection of total iron to be produced (Figure 14), the percentage to be produced each year using hydrocarbon injection (Figure 22), and information that about 1.5 million Btu of hydrocarbon fuels (natural gas or oil) is used per ton of iron produced to obtain Figure 23.

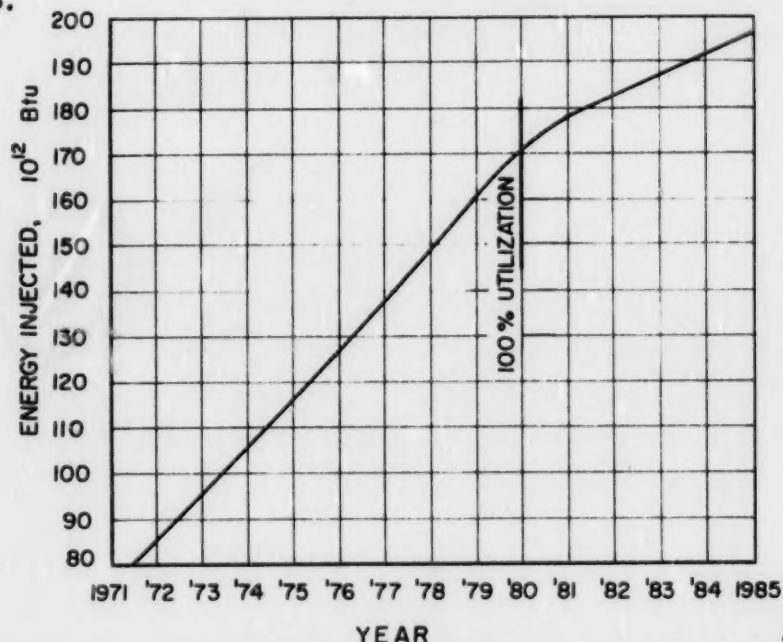


Figure 23. PROJECTION OF ENERGY TO BE CONSUMED IN HYDROCARBON BLAST-FURNACE INJECTION

Figure 23 shows the expected amounts of purchased fuel to be used for blast-furnace injection between 1972 and 1985. Between now and 1980, the amount of purchased fuels used for injection increases about 10.6 million Btu/yr (12% per year). After 1980, the increase in fuels for injection grows at a slower rate of about 4.5 million Btu/yr. The relatively rapid increase in the use of purchased fuels for injection up to 1980 is due to both the growth of iron production and the growth of the percentage of the total iron production made with hydrocarbon injection. After 1980, the growth of hydrocarbon injection tracks the growth of iron production alone, because of "use saturation."

In examining blast-air temperatures for blast furnaces, we found that temperatures were steadily increased over the last 10 years, but are now leveling off. We believe further significant increases are unlikely because they would require major changes in the blast stoves producing the hot air, connecting ductwork, and possibly the blast furnaces themselves. Consequently, we assumed that the energy to heat the blast air to current temperature levels would remain essentially constant from now to 1985.

A typical blast-air stove to produce the hot air uses about 2.25 million Btu of fuel to generate enough air to produce 1 ton of pig iron. In general, blast-air stoves use in-plant gases, and some natural gas and oil are used for load balancing of all plant fuels, for ignition, and during maintenance of the in-plant gas system on these stoves. Historically, the industry has used about 90% in-plant gases and 10% purchased fuels for blast-stove operation. We assumed that this ratio of in-plant to purchased fuel usage would continue to 1985. From the above information, a projection of the amounts of purchased and in-plant fuels (Figure 24) was prepared based on the projected growth of iron production, again shown in Figure 14.

An additional factor that must be considered in the energy-use picture of the blast furnace is the amount of blast-furnace gas that is produced and reused in other plant areas. Predicting the amount of blast-furnace gas that will be produced is somewhat difficult because the amount varies, depending on whether or not hydrocarbon injection is used and on the temperature of the blast air. Data were not available in sufficient detail to account for these variables as a function of the growth in use of hydrocarbon injection, predicted earlier in Figure 22. However, the literature indicated that the difference in blast-furnace-gas production was about 5% between using or not using hydrocarbon injection. We chose to project blast-furnace-gas production as if hydrocarbon injection was used for all ironmaking — an assumption that is really only valid after 1980. Consequently, our projection for blast-furnace gas production before 1980 is probably about 5% high. The projection is shown in Figure 25, which assumes 8.3 million Btu of blast-furnace gas produced per ton of coke charged to the blast furnace. Figure 25 was prepared from the

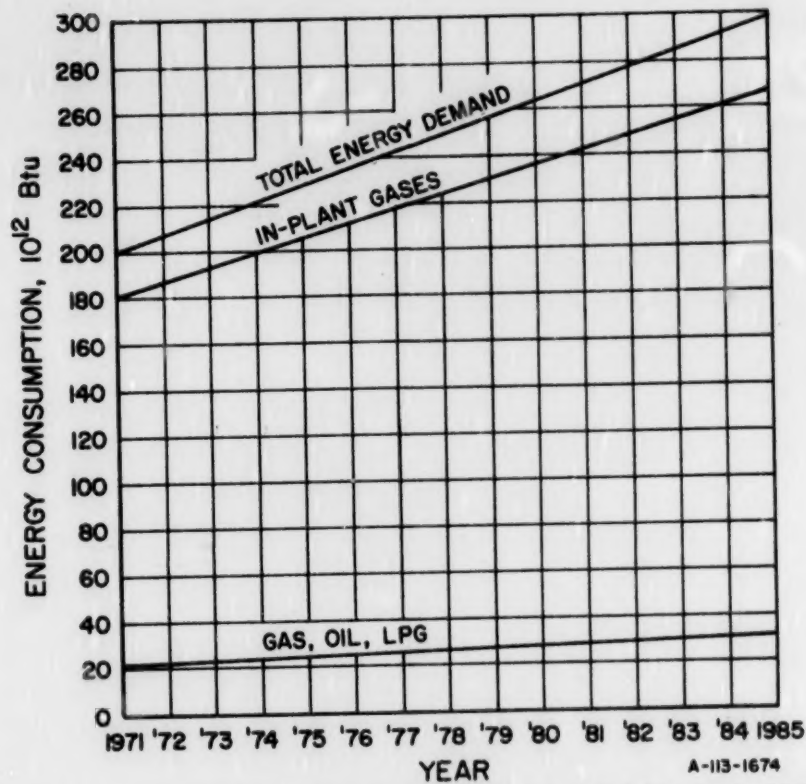


Figure 24. ENERGY CONSUMPTION IN BLAST-AIR STOVES

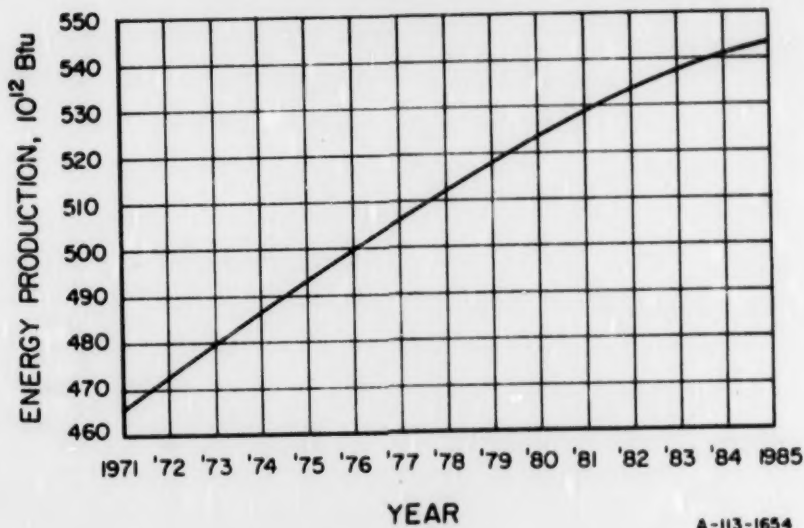


Figure 25. ENERGY PRODUCTION (Blast-Furnace-Gas) FROM BLAST FURNACES

projection of the amount of coke to be used between now and 1985, as shown in Figure 18.

Energy in the form of coke charged to the blast furnace was not considered because it was accounted for in the coking operation in terms of coal usage. In addition, relatively small amounts of oxygen, electric power, and steam are used in the various steps of ironmaking. The energy involved in the production and use of each of these is considered separately in a later section on a plant-wide basis.

Steelmaking Operations

Once pig iron is produced, it is converted to steel in any one of several processes. These processes are the basic oxygen furnace (BOF), the electric-arc furnace, and the open-hearth furnace.

Total Projected Steel Production

Several references that have been found state that the steel industry expects to produce 185.5 million tons of steel in 1985. We estimated the steel production between 1970 and 1985 by linear extension of the industry's prediction for 1985 and actual production in 1970, as shown in Figure 26.

Projected Steel Production by Process

The growth in production of steel by the BOF process has been remarkably linear between 1965 and 1971. We projected future growth (Figure 26) by linear extension of the past growth rate. Production by the electric-arc furnace process also exhibited a linear growth between 1965 and 1971. Again, we projected future growth by a linear extension of past growth.

Projecting the future of the open-hearth furnace process is slightly more complex. Open hearths are being phased out of use because of a variety of problems discussed earlier in this report. Information from the steel industry indicates that the rate of phaseout depends on the number of furnaces that reach the end of their useful life each year. The useful life of an open hearth is estimated at about 20 years. Based on the rate of construction prior to 1965 and the rate of decline or phaseout after 1965, we determined that open-hearth production will decline at a

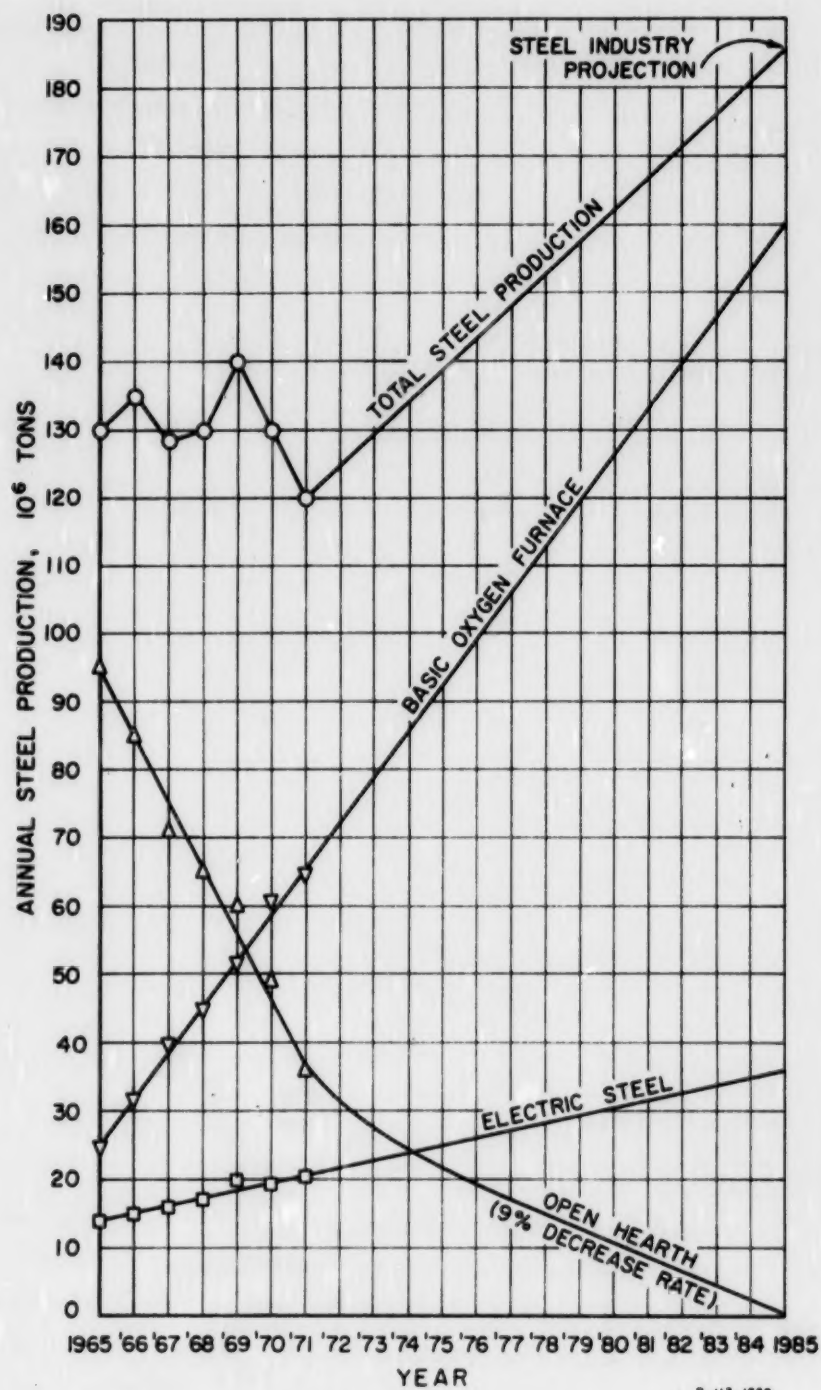


Figure 26. PROJECTED ANNUAL STEEL PRODUCTION TO 1985

rate of about 9% per year, with the newest furnaces going out of service about 1985, as shown in Figure 26.

As a means of checking the validity of our projections for each of the three steelmaking processes, the projected production for each year was totaled and compared with the projection of total steel production, which was independently derived. The agreement was satisfactory, as shown in Table 7.

Table 7. COMPARISON OF TOTAL PROJECTED STEEL PRODUCTION WITH SUM OF PROCESS PRODUCTION PROJECTIONS

Year	Production				Total Production	Difference
	BOF	EF*	OH [†]	Total		
	10 ⁶ tons/yr					
1971	65	20.5	37	122.5	120	-2.5
1972	72.4	21.5	32	125.9	125	-0.9
1973	79	22.6	28	129.6	129.5	-0.1
1974	86	23.7	24.6	134.3	134.2	-0.1
1975	92.5	24.8	21.8	139.1	139	-0.1
1976	99.4	26.0	19.4	144.8	143.5	+1.3
1977	106	27.0	17	150	148	+2.0
1978	113	28.0	15	156	154	+2.0
1979	119.8	29.0	12.8	161.6	159	+2.6
1980	126.5	30.2	10.8	167.5	163	+4.5
1981	133	31.4	8.6	173.0	168	+5.0
1982	140	32.5	6.5	179.0	172	+7.0
1983	146.6	33.5	4.5	184.6	177	+7.6
1984	153.5	34.6	2.4	190.5	182	+8.5
1985	160	35.7	0	195.7	186	+9.7

* Electric-arc furnace.

† Open-hearth furnace.

Energy Usage in the Open-Hearth Process

The open-hearth process was designed so that it could use a very wide range of fuels, from in-plant gas, natural gas, and oil to tar and pitch. As in other processes already discussed, we again found that the ratio of in-plant gas usage to purchased fuel usage was fairly constant between 1965 and 1971. The split between fuels for these years was 14% in-plant gas usage and the remainder purchased fuels. In addition, the total average energy requirement for open-hearth steelmaking is 3.55

million Btu/ton of steel. Based on these findings and the data of Figure 26, we projected the decline in energy requirements, as shown in Figure 27.

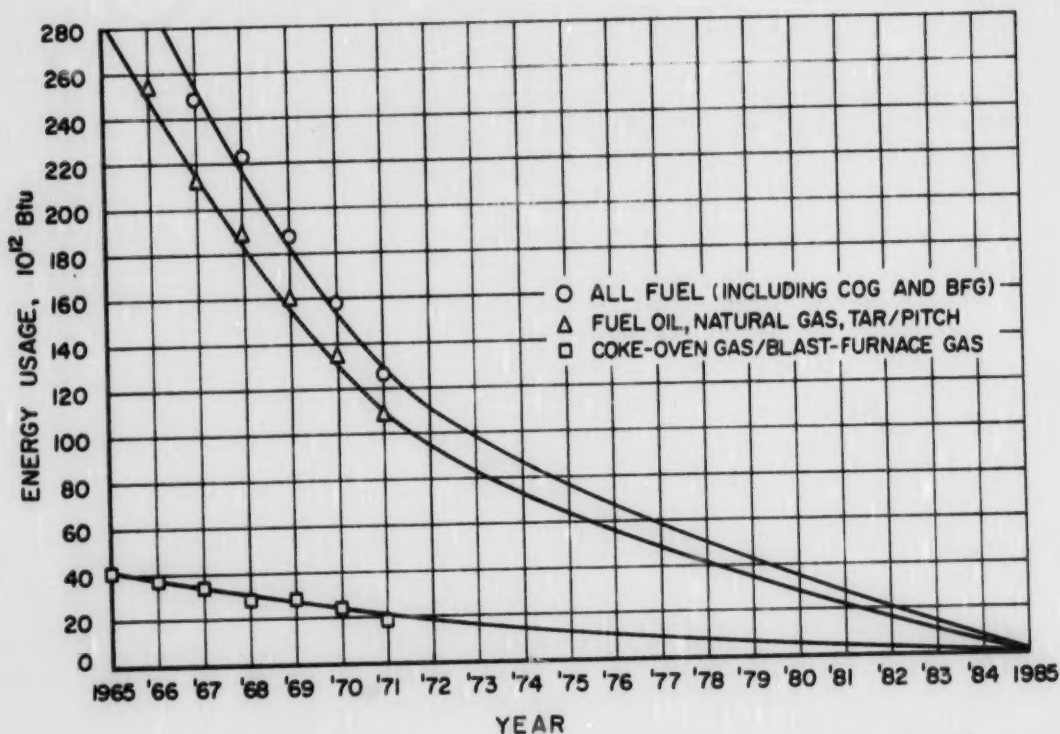


Figure 27. PROJECTED DECLINE OF ENERGY USE IN OPEN-HEARTH STEEL-MELTING FURNACES

Energy Usage in the BOF Process

Very little fossil fuel is used in the BOF process; all the actual processing heat is supplied by the exothermic reaction of the iron and oxygen. Fossil fuels generally are used only between charges or heats to maintain vessel temperature and, maybe some small amounts, during pouring. An industry average for the amount of fossil fuel used in the BOF process is 200,000 Btu/ton of steel, which was calculated from reported fuel use and production data for the years 1965 to 1971. By using the above heat requirement and the projected production of steel by the BOF process (Figure 26), fossil-fuel consumption was projected to the year 1985 and is shown in Figure 28.

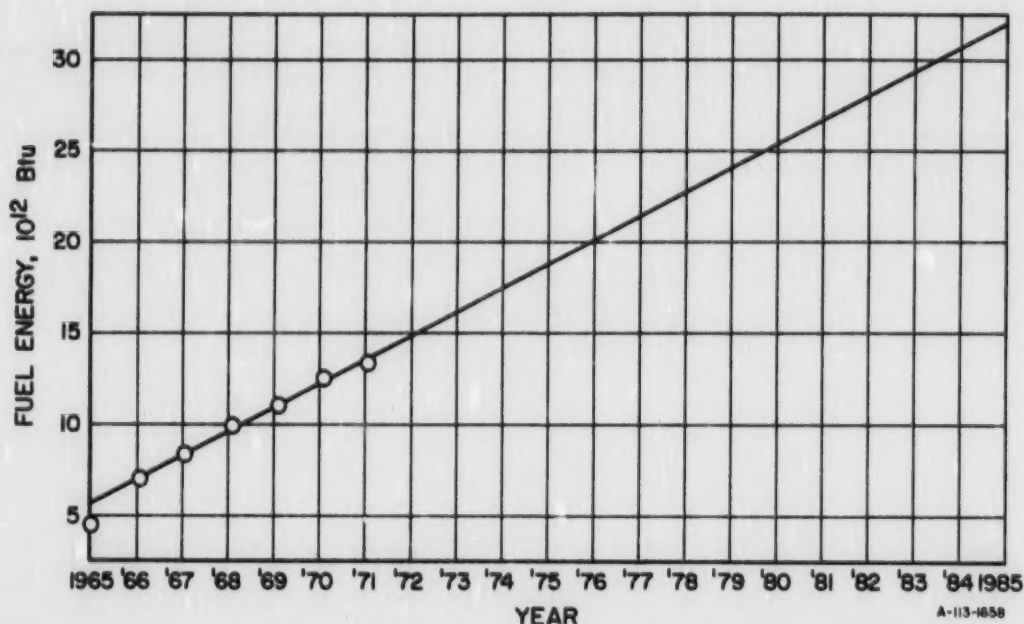


Figure 28. PROJECTED ENERGY CONSUMPTION OF FOSSIL FUELS IN PRODUCTION OF STEEL BY THE BOF PROCESS (Primarily Heat Used Between Charges)

Fossil fuels are indirectly used in the BOF steel process in the form of the oxygen used to react with the iron. Fossil fuels are converted to electrical energy, which in turn is used to make the oxygen. Later in this report, the amount of fossil-fuel energy necessary to make the oxygen is considered and included in the overall energy picture of the steel industry.

Energy Usage in the Electric-Arc Furnace Operation

The literature indicates that the electric steelmaking process uses about 1.7 million Btu of energy (electrical) per ton of steel produced. Based on these data and the projection of steel to be produced by electric furnaces, we projected the energy needs for this process to 1985. The amounts of fossil fuels required to produce the needed electric power are considered in a later section. However, the projection of electric energy required is shown in Table 8.

Table 8. PROJECTED ELECTRIC POWER REQUIREMENTS FOR
ELECTRIC FURNACE OPERATION FROM 1973 TO 1985

<u>Year</u>	<u>Projected Steel Production, 10⁶ ton/yr</u>	<u>Projected Power Required, 10¹² Btu/yr</u>
1973	24	40.8
1975	26	44.2
1977	29	44.3
1979	31	52.7
1981	34	57.8
1983	37	62.9
1985	40	68

Finished-Product Steel Processing

Finished-product steel processing, in this analysis, includes all the steps from the time molten steel is available to producing typical steel plant products. All these steps are grouped into one or the other of two basic processes: reheat and form or continuous casting. When steel is processed by what we call reheat and form steps, it is first cast into an ingot, allowed to partially or completely cool, reheated in soaking pits and rolled to smaller dimensions, again allowed to partially or completely cool, and reheated again and subjected to additional form changes.

This process of reheat and form can occur only once or several times, depending on the end product desired. Therefore, it would be extremely complex to calculate energy consumption by considering the individual furnace processes that may be involved. However, average energy data are available on all heating operations as one average operation but including continuous casting. Once the amount of heat used for continuous casting operations is subtracted, we obtain the average energy required for the reheat and form process on a per-ton-of-steel-produced basis.

Continuous Casting and Conventional Reheat Production

In the continuous casting process, the molten steel from the BOF, open-hearth, or electric-arc furnace is formed directly into a finished or semifinished product. This process bypasses the normal steps of cast, cool, reheat, cool, etc. Continuous casting in the U.S. is very new and consequently represents only a small portion of the steel processing currently being done. In 1971 only 4.0% of all steel processed

in the U.S. was continuously cast. However, the steel industry predicts that 20% of all steel will be continuously cast by 1985. Based on current continuous cast production and this prediction, a linear growth in the use of continuous casting was assumed in terms of the percentage of total steel produced (Figure 29).

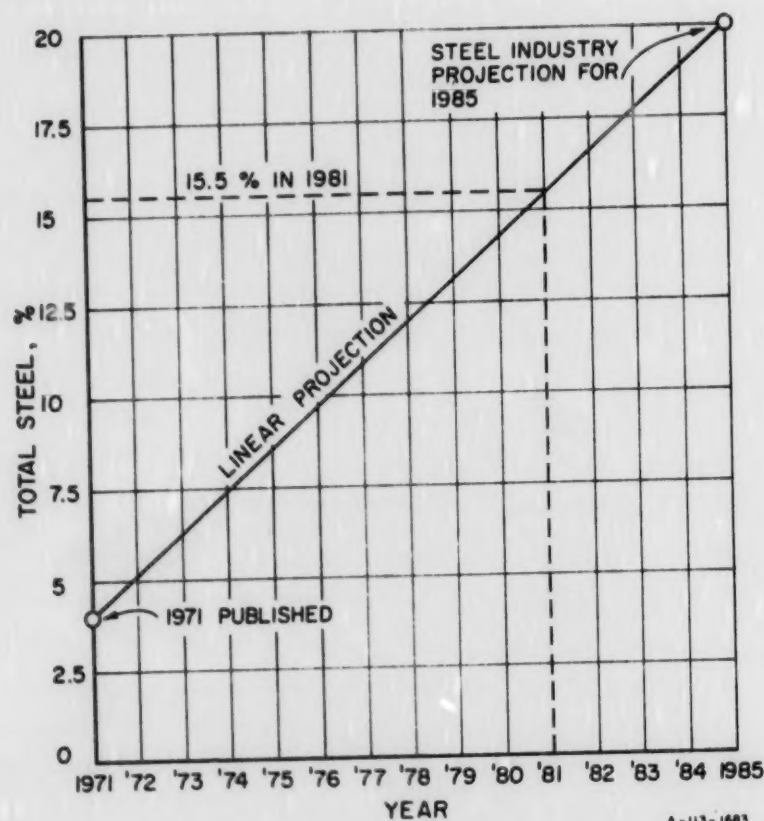
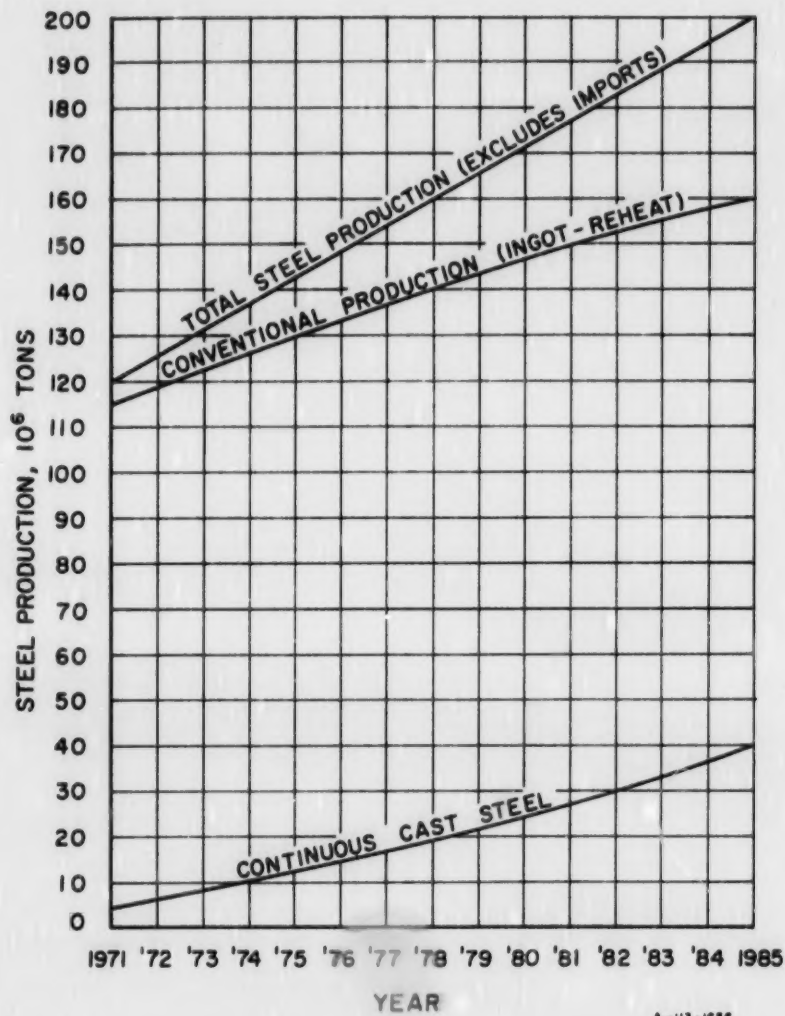


Figure 29. LINEAR PROJECTION OF CONTINUOUSLY CAST STEEL AS A PERCENTAGE OF TOTAL STEEL PRODUCED

Therefore, we were able to project the amount of steel to be continuously cast between 1971 and 1985 from the projected total steel production given in Figure 26 and again in Figure 30. The difference between the amount of continuous cast steel and total steel production gives the amount of steel that must be processed by the conventional means of reheat and form. We realize that some continuous cast steel is reheated later for final finishing. However, the literature suggests that the quantities are relatively small. We are therefore not considering this aspect.



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Figure 30. PROJECTED GROWTH OF CONTINUOUS CASTING AND CONVENTIONAL PRODUCTION OF STEEL

Continuous Casting and Conventional Reheat Energy Requirements

Continuous casting requires only moderate amounts of fuel for heating transfer ladles, spouts, and portions of the casting equipment. Current equipment requires about 250,000 Btu/ton of steel cast, and the fuel is usually natural gas. Table 9 shows the projected amount of natural gas to be used for continuous casting between 1971 and 1985 based on the projected production of continuous cast steel.

Table 9. PROJECTED ENERGY REQUIREMENTS
FOR CONTINUOUS CASTING

<u>Year</u>	<u>Production, 10⁶ tons</u>	<u>Energy, 10¹² Btu</u>
1971	4.8	1.2
1973	8.4	2.1
1975	12.2	3.05
1977	16.9	4.23
1979	21.8	5.45
1981	27.3	6.81
1983	33.3	8.31
1985	40.0	10.0

The average amount of energy used to process steel in the conventional reheat and form steps has cycled from a low of 4.3 to a high of 4.8 million Btu/ton over the last 6 years. An average for this time period was 4.7 million Btu/ton, which was used as the basis for future projections shown in Figure 31.

General Energy Uses

Several energy-use areas in the steel industry cannot be tied to any one processing step. Steam, electric power, and oxygen are inter-related and used throughout the mill. Therefore, this report deals with these energy sources in this separate section. None of these items are energy in the usual sense, but substantial amounts of fossil fuels are used in their production.

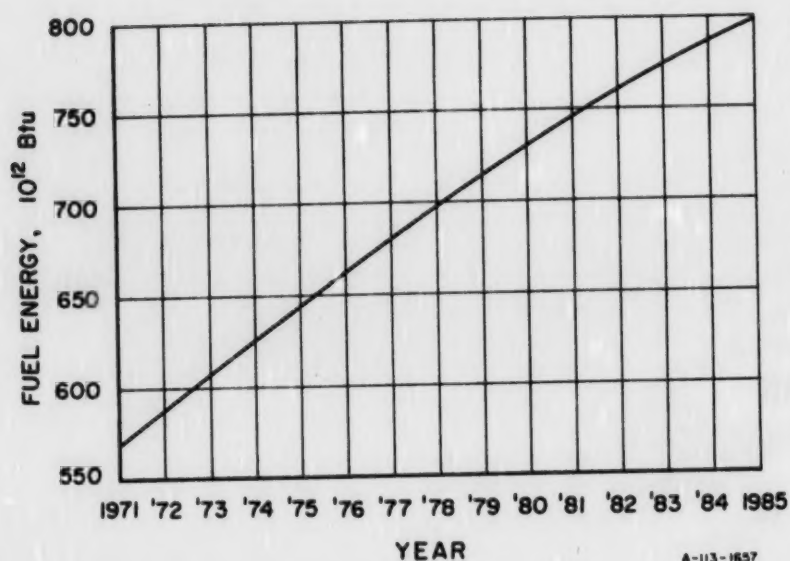


Figure 31. PROJECTED FUEL ENERGY REQUIREMENTS
FOR STEEL REHEATING AND CONTINUOUS CASTING

Production and Use of Oxygen

The major uses of oxygen in an integrated steel mill are for the BOF process, the open-hearth furnace, blast-furnace injection, scarfing, electric-arc melter injection, and general steel cutting with gas-oxygen torches. The oxygen requirements of each of these processes were discussed earlier in this report. The amounts of oxygen required by each of these processes on a production rate basis are given in Table 9.

Table 10. PROCESS OXYGEN REQUIREMENTS

<u>Process</u>	<u>Oxygen Requirement, ton /ton product</u>
BOF Process	0.0789
Open-Hearth Furnace	0.0451
Electric-Arc Furnace	0.0137
Blast-Furnace Injection	0.0067
General Plant Usage	0.0095

Based on this information and on production predictions, we have projected the individual demands of each process for oxygen (Figure 32).

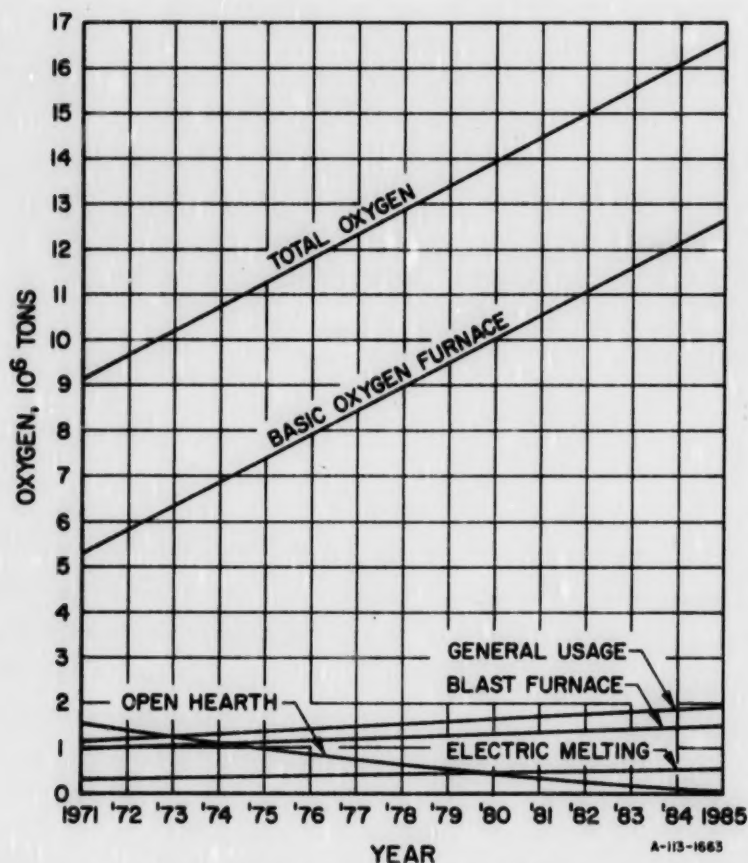


Figure 32. PROJECTED STEEL INDUSTRY DEMAND FOR OXYGEN AS A FUNCTION OF PROCESS TYPE

The need for oxygen in the BOF process will increase from about 6.4 million tons in 1973 to 12.6 million tons in 1985; in other words, it will almost double. The use of oxygen for open-hearth injection will decline with the decline in open-hearth usage. In 1973, only 1.2 million tons of oxygen was used by open hearths; this is expected to decline to 0 by 1985. Blast-furnace injection of oxygen and the demand for oxygen in electric melting will increase slightly, but not as strongly as for the BOF process. The amount of oxygen required for general plant usage was derived from consumption data for 1966 to 1971. Published data for general-plant oxygen usage divided by steel production in each year showed that requirements in this area are 0.0095 ± 0.0003 ton of oxygen/ton of steel produced.

The individual projections of oxygen demand by process were summed to obtain a total demand projection (Figure 32). This summation predicted that the total demand for oxygen will grow from about 9.2 million tons in 1971 to 16 million tons in 1985. The calculated demand for oxygen in 1971 of 9.2 million tons agrees well with published data, which show an actual usage of 9.14 million tons.

Only a small portion of the oxygen used by the steel industry is produced in oxygen plants owned by the steel plant. In 1967, this so-called "self-produced" oxygen accounted for only about 8.8% of the total amount used. However, between 1967 and 1971, the steel industry has built and operated an increasing number of oxygen plants. Figure 33 shows the amount of self-produced oxygen produced between 1967 and 1971 in terms of the percentage of total oxygen used. The trend toward increasing amounts of self-produced oxygen was projected to 1985 with a linear extrapolation. The data of Figure 32 (projected demand) and Figure 33 (percentage self-produced) were used to calculate the quantities of oxygen to be purchased and the quantities to be self-produced (Figure 34).

Oxygen usually is produced by liquefaction of air, which requires a total of about 340 kWhr of electric power per ton of oxygen. If the oxygen is to be stored, in part, as a liquid, about 750 kWhr of electric power is required per ton of oxygen. Self-generated oxygen usually is produced and used without the liquid storage step. Only small amounts of storage are required to adjust for daily production fluctuations. Purchased oxygen

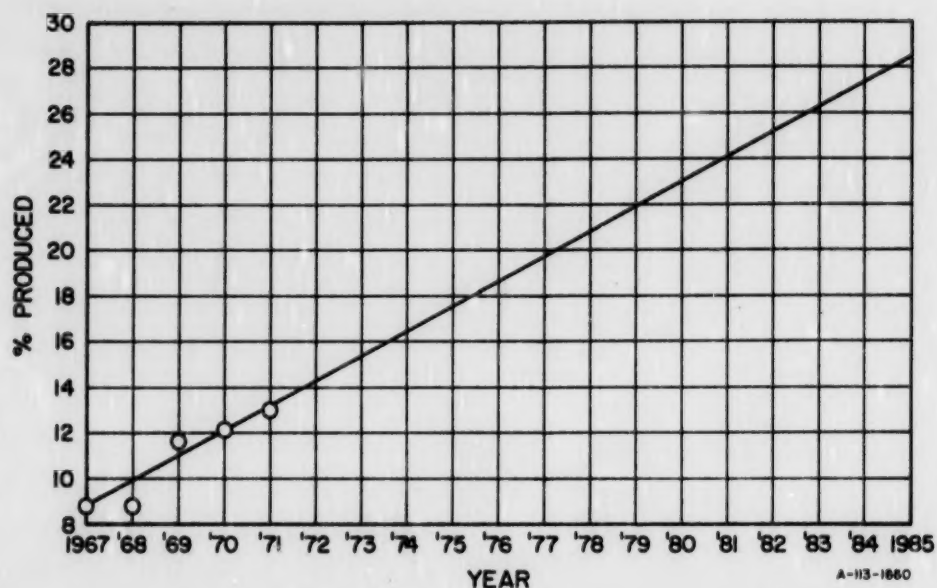


Figure 33. PROJECTED PERCENTAGE OF OXYGEN PRODUCED BY STEEL INDUSTRY FOR PLANT CONSUMPTION

usually is liquefied for ease of transport by truck or cryogenic pipeline. Therefore, the calculation of energy usage for making self-produced oxygen was based on 340 kWhr of power, and that for purchased oxygen was based on a power requirement of 750 kWhr/ton of oxygen (Figure 34).

The quantity of fossil fuels used to generate the electric power that, in turn, is used to make the oxygen, is considered in the next section.

Production and Demand for Electric Power and Steam

Published information for 1962 to 1971 shows that electric consumption for general plant use (excluding electric melting and oxygen production) correlates closely with steel production. These data show that 0.98-1.09 million Btu of electric power is used per ton of steel produced. Based on the average consumption of 1.06 million Btu/ton of steel and our earlier projection of steel production, general plant electric requirements were predicted (Figure 35) to 1985. This projection shows that general plant electric consumption will grow from 128 trillion Btu/yr in 1971 to 212 trillion Btu/yr in 1985. The electric energy requirements

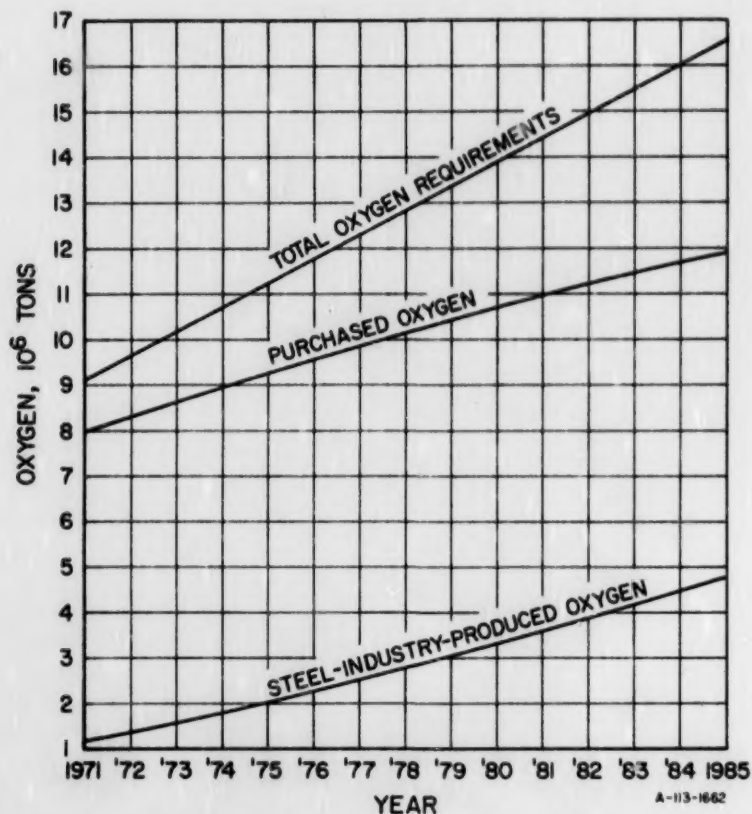


Figure 34. PROJECTED OXYGEN REQUIREMENTS WITH RELATIVE AMOUNTS OF PURCHASED AND SELF-PRODUCED OXYGEN

and production projections discussed earlier were used to predict demands for electric melting and self-produced oxygen. The electric demand of these three areas was summed to estimate total electric power demands.

Electric power is much like oxygen production; that is, a portion of the demand is satisfied by in-house production and some power is purchased. Historical data on self-produced power (Figure 36) from 1967 to 1971 show a strong trend toward purchasing electric power. The percentage of total electric power to be self-produced from 1971 to 1985 was estimated from a linear extrapolation. This resulted in a calculated self-produced electric power projection that showed generation capacity declining from 38 trillion Btu in 1971 to about 0 in 1985 (Figure 37), assuming 3.23 Btu of fuel energy per Btu of electric energy produced.

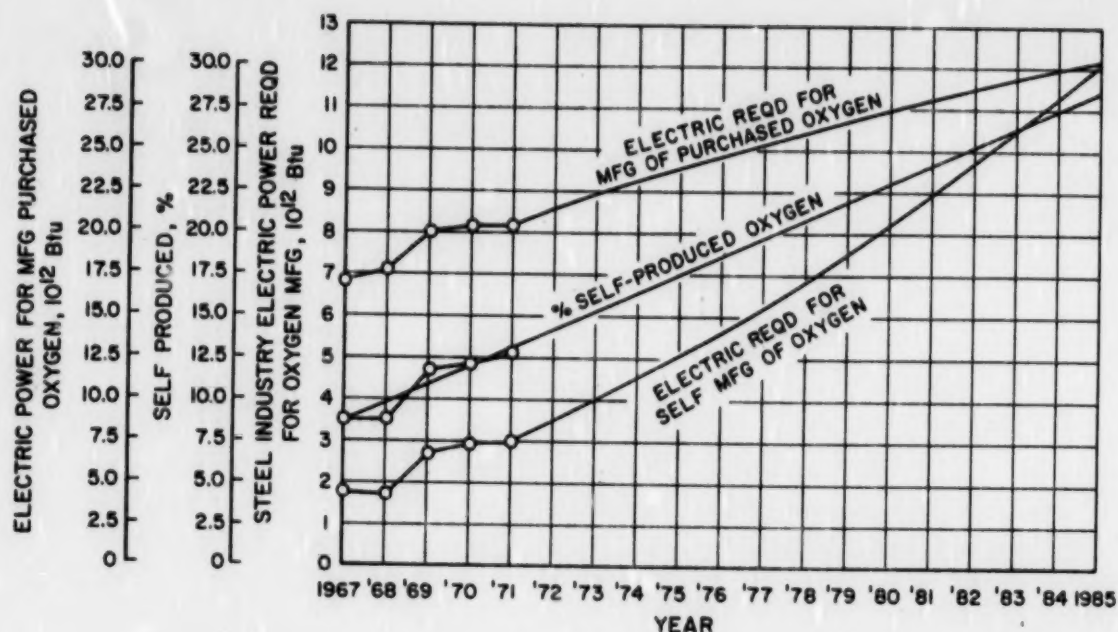
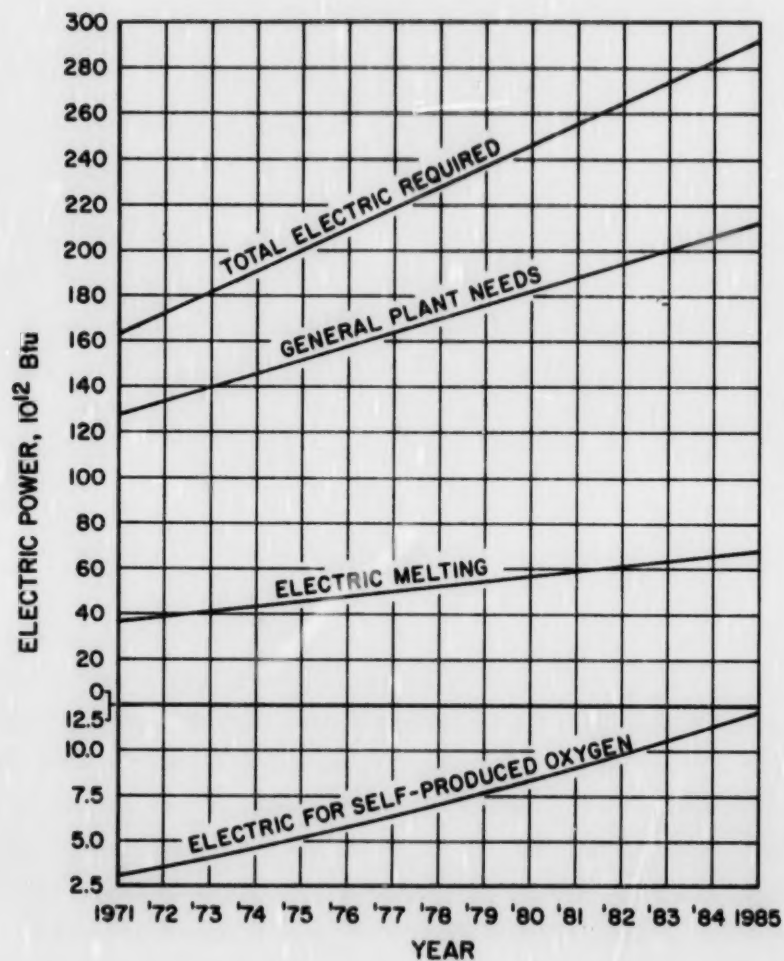


Figure 35. PROJECTION OF ELECTRIC POWER REQUIREMENTS FOR PRODUCING OXYGEN REQUIRED BY STEEL INDUSTRY

In addition to electric power, process steam is produced in boilers; this requires, historically, about 1.7 million Btu of fuel energy per ton of steel produced. Based on the projected total steel production (Figure 29) and the average energy required for producing process steam, Figures 38 and 39 were prepared to show the amounts of fuel required between 1971 and 1985. Figure 40 shows the projected total amount of fuel energy for use in steel industry boilers, including both electric power and process steam. The increase in fuel demand for boilers increases very little from 1971 to 1981 and declines from 1981 to 1985. This is caused by the combination of growth in the demand for steam and the decline in self-generated electricity production.

Fuel Types and Demand for Boilers

The steel industry boiler can readily operate on in-plant gases, coal, oil, or gas. We assumed that all available in-plant gases would be used first with purchased fuels used to make up any differences to meet the energy demand.



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Figure 36. PROJECTED REQUIREMENTS FOR ELECTRIC POWER

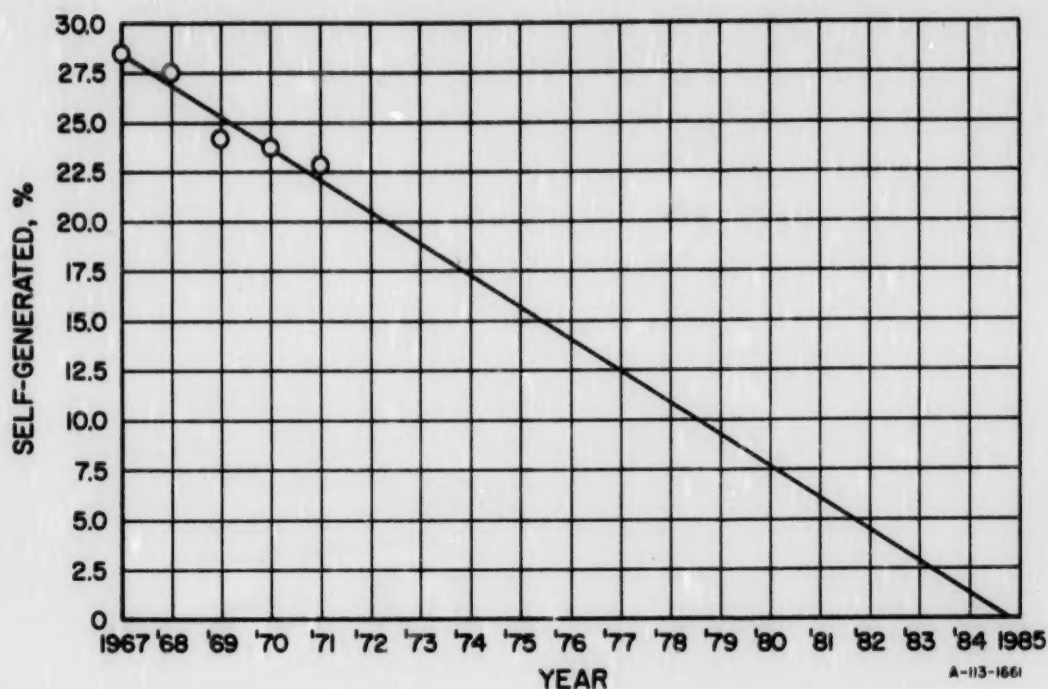


Figure 37. RATE OF DECLINE (Linear Projection) OF STEEL-INDUSTRY-GENERATED ELECTRIC POWER

Earlier in this report, we indicated the amounts of in-plant gases that would be produced by the coke ovens and blast furnaces in terms of Btu/ton of iron, with the necessary corrections for changes in coke requirements, etc. From these data, we prepared a projection of total in-plant production of fuel gases (Figure 41). In 1971, steel industry records show that 854 trillion Btu of in-plant gases was produced. Our projection indicates that the production of gases will increase, but at a declining rate. Approximately 1 billion Btu will be produced in 1985. Data presented earlier in this report also indicated the total amount of energy needed by each iron and steel process and a typical split between the use of in-plant gases and purchased fuels. This information was used to calculate the use of in-plant gases for all processes other than in boilers. These data are shown in Figures 42, 43, and 44. Figure 42 shows the projected demand for in-plant gases for steel reheating and continuous casting based on the total energy requirements of these processes as shown

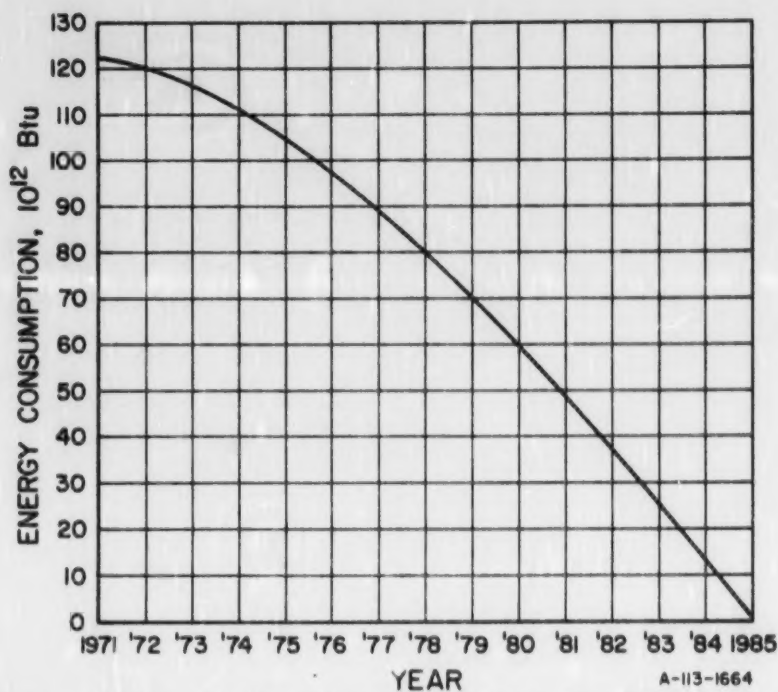


Figure 38. ENERGY REQUIREMENTS FOR BOILERS TO PRODUCE PROCESS STEAM FOR THE IRON AND STEEL INDUSTRY

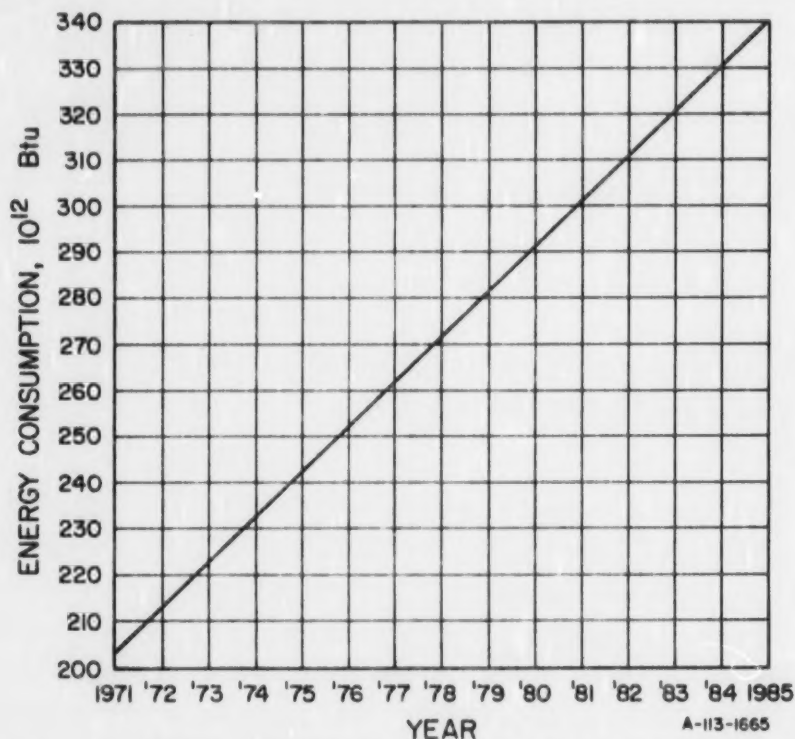


Figure 39. ENERGY REQUIREMENTS FOR BOILERS TO PRODUCE ELECTRIC POWER FOR THE IRON AND STEEL INDUSTRY

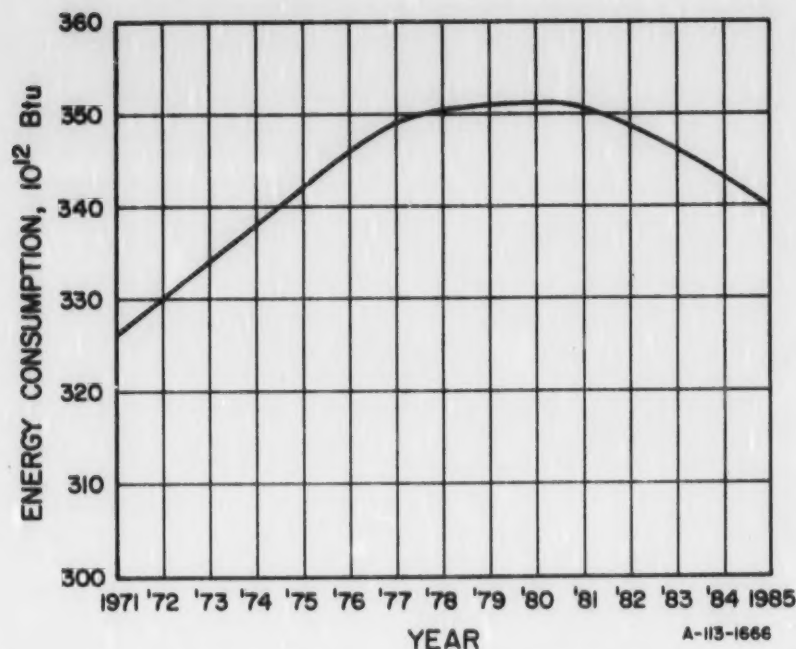


Figure 40. TOTAL FUEL ENERGY REQUIREMENTS FOR STEEL INDUSTRY BOILERS (Steam and Electric Power)

in Figure 29 and the historical split between fuel types. Figure 43 shows the total in-plant gases required from ore preparation through pig iron production. Figure 44 shows the in-plant gases remaining after subtracting ore preparation to iron production and what is used for steel reheat and continuous casting. Figure 44 also shows the demand for in-plant gas for steel finishing processes and the resulting supplies for boiler fuel. Subtracting the availability of in-plant gas from the total projected demand for boiler fuel uses yields the total amounts of purchased fuels needed (Figure 45).

The purchased fuel used by boilers can be coal (boiler grade), oil, or gas. In 1971, the industry used 109 trillion Btu of coal in its boilers; this matches the total purchased needs for boilers, as shown in Figure 45. However, there has been a strong trend toward replacing coal firing with other purchased fuels, probably because of pollution regulations. We cannot be sure this trend will continue because of the current shortages of oil and gas. However, for this analysis, the trend was assumed to

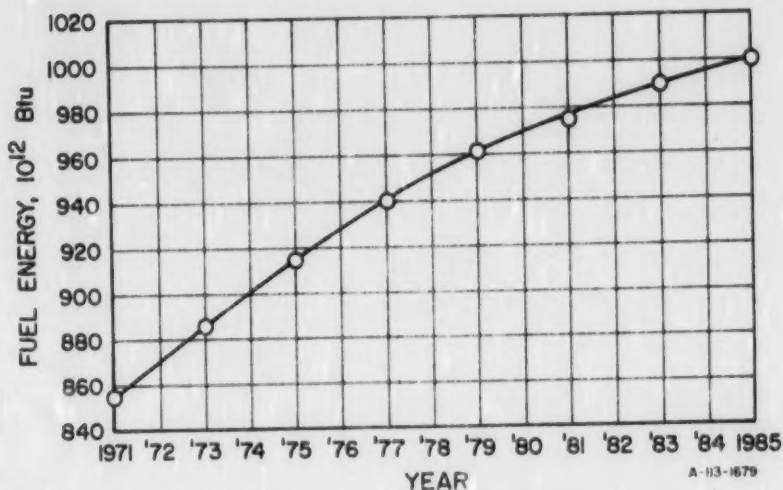


Figure 41. PROJECTED TOTAL PRODUCTION OF IN-PLANT GASES (Coke-Oven Gas and Blast-Furnace Gas) FROM IRONMAKING PROCESS

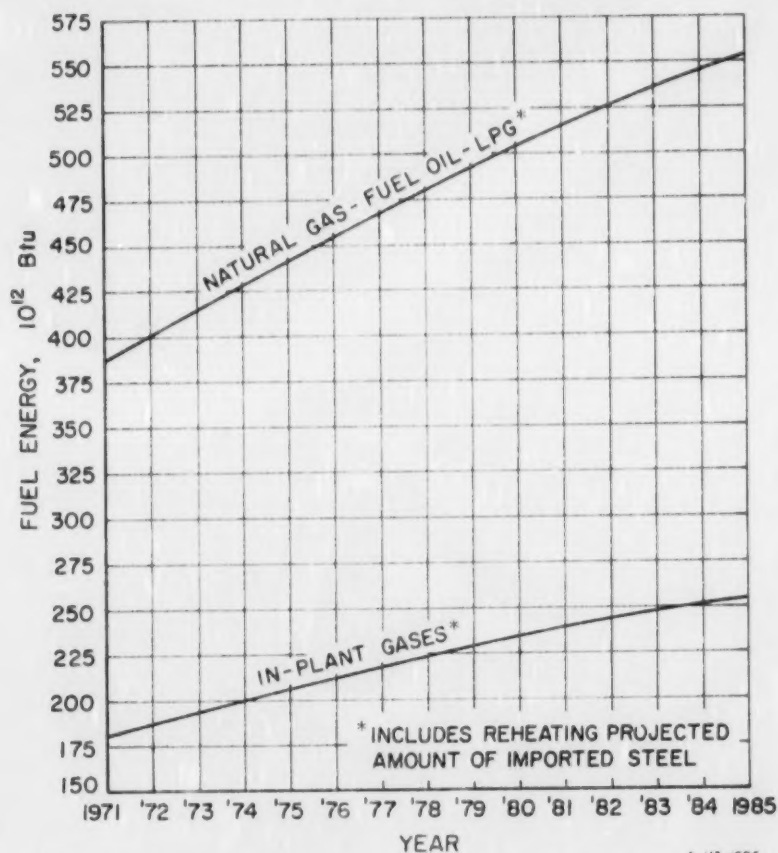
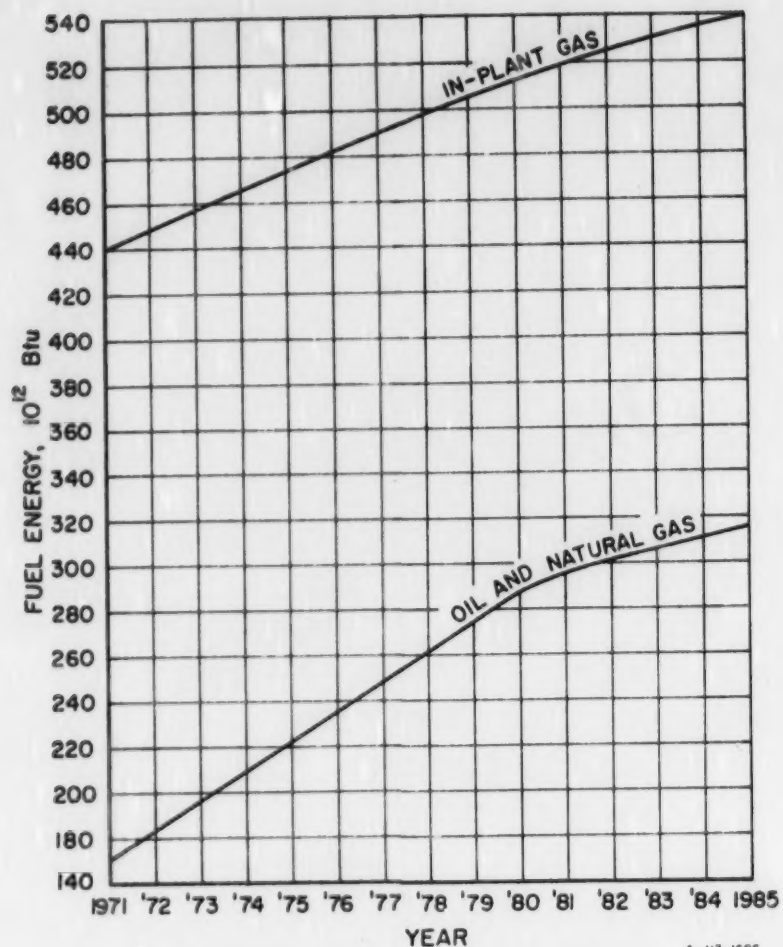


Figure 42. PROJECTED DEMAND FOR IN-PLANT GASES AND HYDROCARBON FUELS (Excluding Coal) FOR STEEL REHEATING AND CONTINUOUS CASTING OPERATIONS
IX-73



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Figure 43. PROJECTED DEMAND FOR OIL, NATURAL GAS, AND IN-PLANT GASES (Coke-Oven Gas and Blast-Furnace Gas) FROM ORE PREPARATION TO PIG IRON PRODUCTION

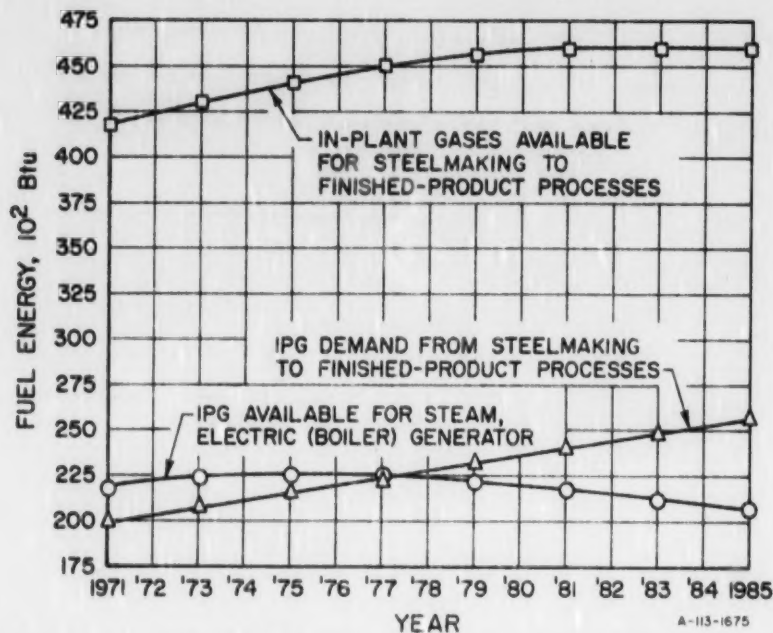


Figure 44. BREAKDOWN OF IN-PLANT GAS USE FOR STEELMAKING TO FINISHED PRODUCT PROCESSES AND FOR USE TO GENERATE STEAM, ELECTRIC POWER, AND MISCELLANEOUS PROCESS HEAT

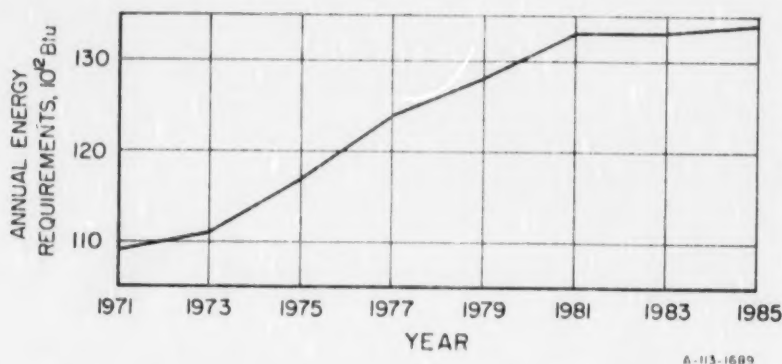


Figure 45. HYDROCARBON FUELS NEEDED FOR BOILER MAKEUP

continue. Historically, the use of boiler-grade coal in the steel industry has declined at a rate of 9% per year between 1965 and 1971. Projecting this decline to the year 1985 yielded the data shown in Figure 46.

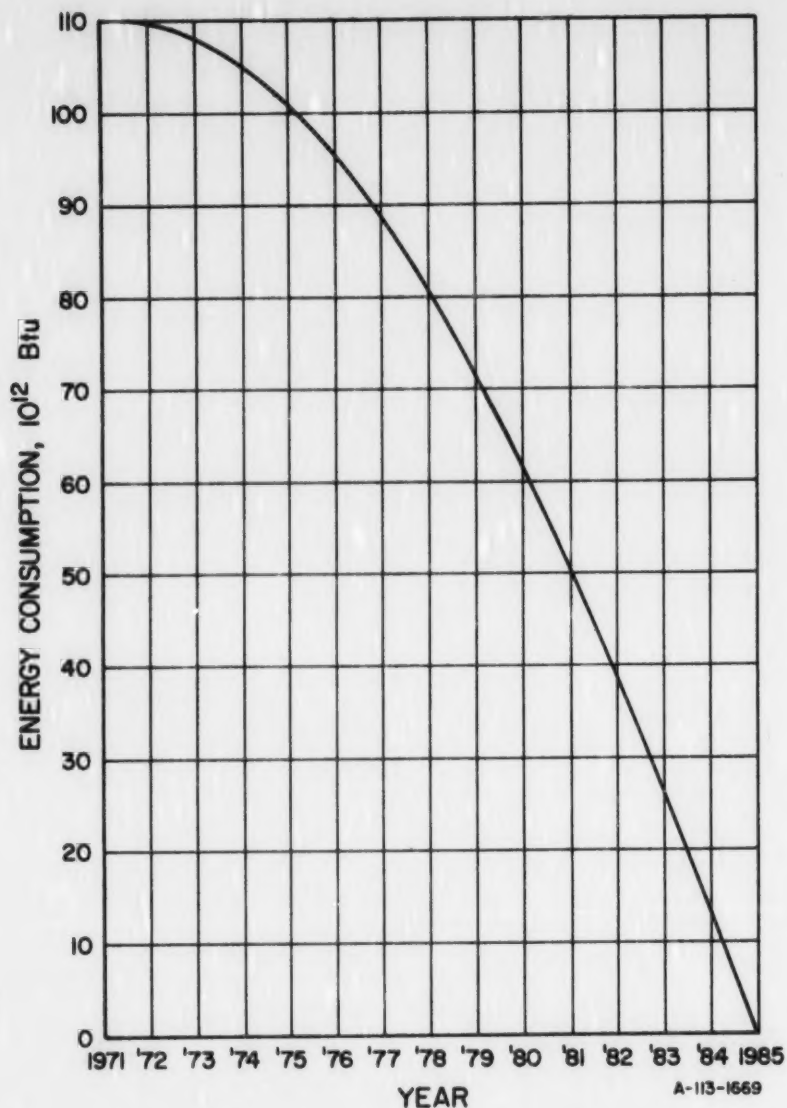


Figure 46. PROJECTION OF COAL ENERGY DEMAND FOR OPERATING STEEL INDUSTRY BOILERS

By subtracting the coal usage projected in Figure 46 from the projected total demand for purchased fuels (Figure 45), we were able to estimate the demand for oil and gas for boilers, as shown in Figure 47.

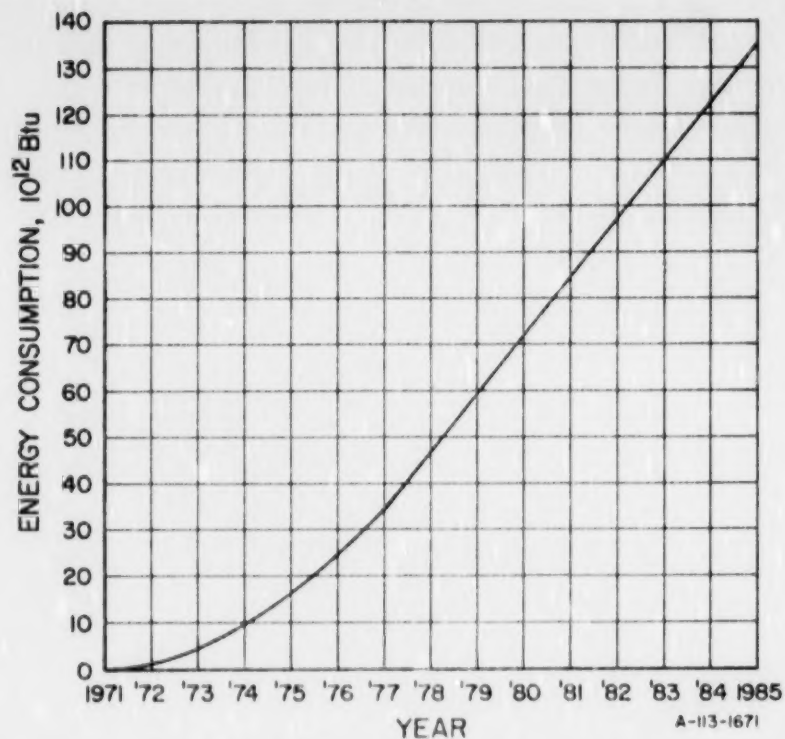
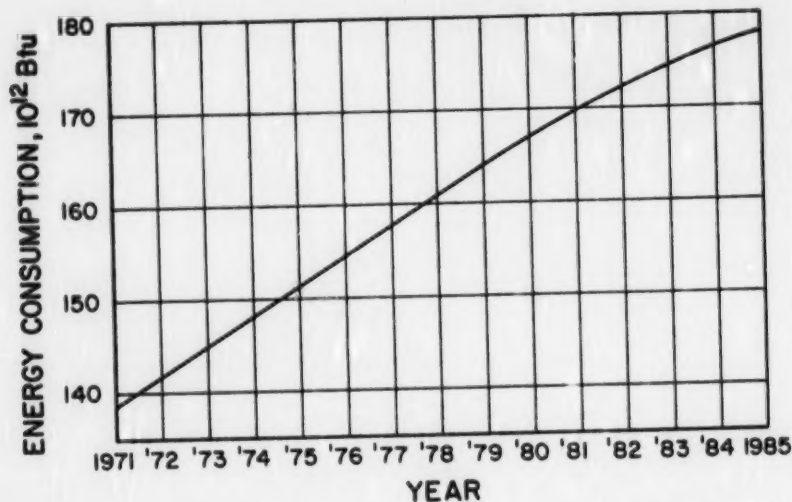


Figure 47. PROJECTION OF OIL AND GAS ENERGY DEMAND FOR OPERATING STEEL INDUSTRY BOILERS

Miscellaneous Uses of Energy

The iron and steel industry uses significant quantities of energy for such things as flame cutting of steel and direct-fired space heating. The uses are too numerous to project energy consumption on an individual basis. However, the total consumption of energy for these so-called "other uses" historically is about 10.5% of all process energy, excluding coal for coke and boiler fuel. Based on the assumption that this ratio would be maintained, Figure 48 was prepared to project the need for "other uses" based on a summation of projected energy demand by all processes presented in earlier figures. Almost all this fuel is oil, natural gas, or liquid propane.



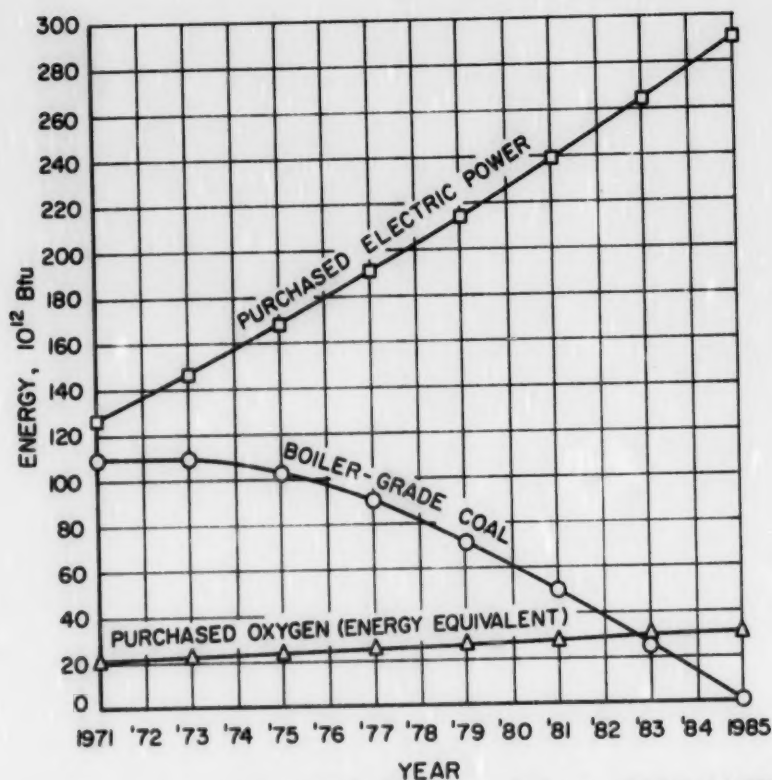
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Figure 48. PROJECTED DEMAND FOR HYDROCARBON FUELS FOR "OTHER" PLANT USES

Summary of Energy Demand Projections

Summing all the energy demand projections of this discussion yields the following conclusions. Between 1973 and 1985 -

- The demand for steel industry boiler-grade coal will drop from about 108.6 trillion Btu/yr to about 0 (Figure 49).
- The demand for fuel energy to make the oxygen purchased by the steel industry will grow from about 20.4 to 30.2 trillion Btu (Figure 49).



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Figure 49. PROJECTION OF TOTAL PURCHASED ELECTRIC POWER, BOILER-GRADE COAL, AND PURCHASED OXYGEN (Energy Equivalent) ENERGY

- The demand for fuel energy to make the electric power purchased by the steel industry will grow from about 128 to about 292 trillion Btu (Figure 49).
- The demand for hydrocarbon fuel by the steel industry will grow from about 3150 to about 3572 trillion Btu (Figure 50), and coal for coking will be about 66% of this demand, as shown in Figure 49.

Environmental Impact Pattern - Projections to 1985

The preceding section presented projections of energy consumption based on the implementation of new technology, the phasing out of several processes, and the growth of some existing processes. The combined effect of the energy consumption and production of each process will determine the ultimate impact on the environment by the iron and steel industry. The projected emission levels of each of the process areas are discussed below.

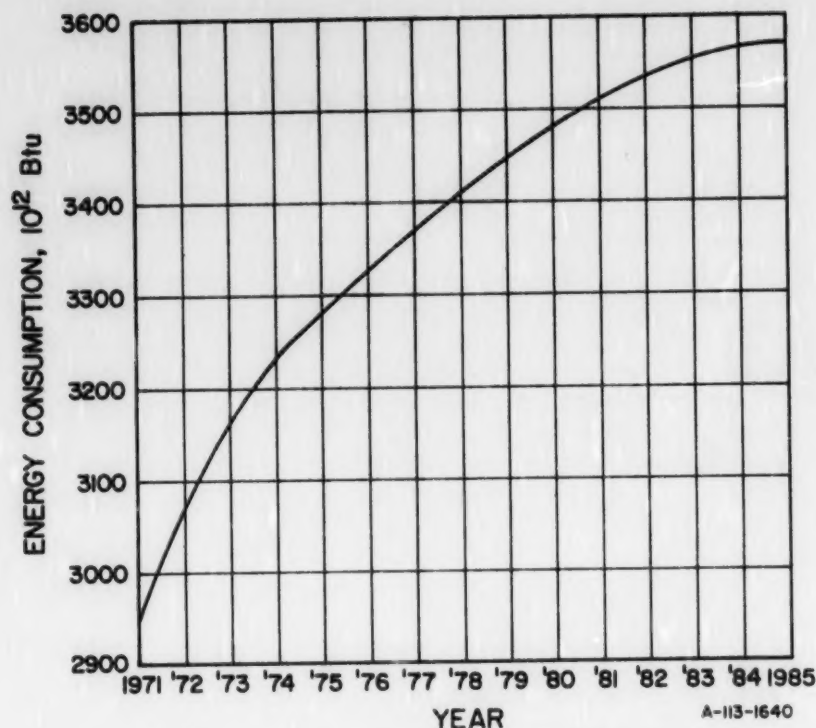


Figure 50. PROJECTION OF DEMAND FOR ALL PURCHASED FOSSIL FUELS

Particulate Emissions

Information on particulate emissions was obtained for iron and steel processes both using and not using stack cleanup equipment. The processes producing the major portion of all emissions are sintering of ore, pelletizing of ore, coke-manufacturing, open-hearth furnace, basic oxygen furnaces, and electric-arc furnaces. Many other processes, such as steel reheat furnaces, blast air stoves, etc., emit particulate emissions; however, the steel industry estimates that these total less than 0.5% of all emissions. Consequently, these emissions were not specifically considered in this analysis.

Table 5 showed the typical particulate emission rates of each iron-making process. Based on these data, the emission projections of Figures 51 and 52 were calculated. Figure 51 shows the annual emission rate for the steel industry with stack cleanup systems. Several assumptions were necessary to calculate the emission rate of open-hearth furnaces and

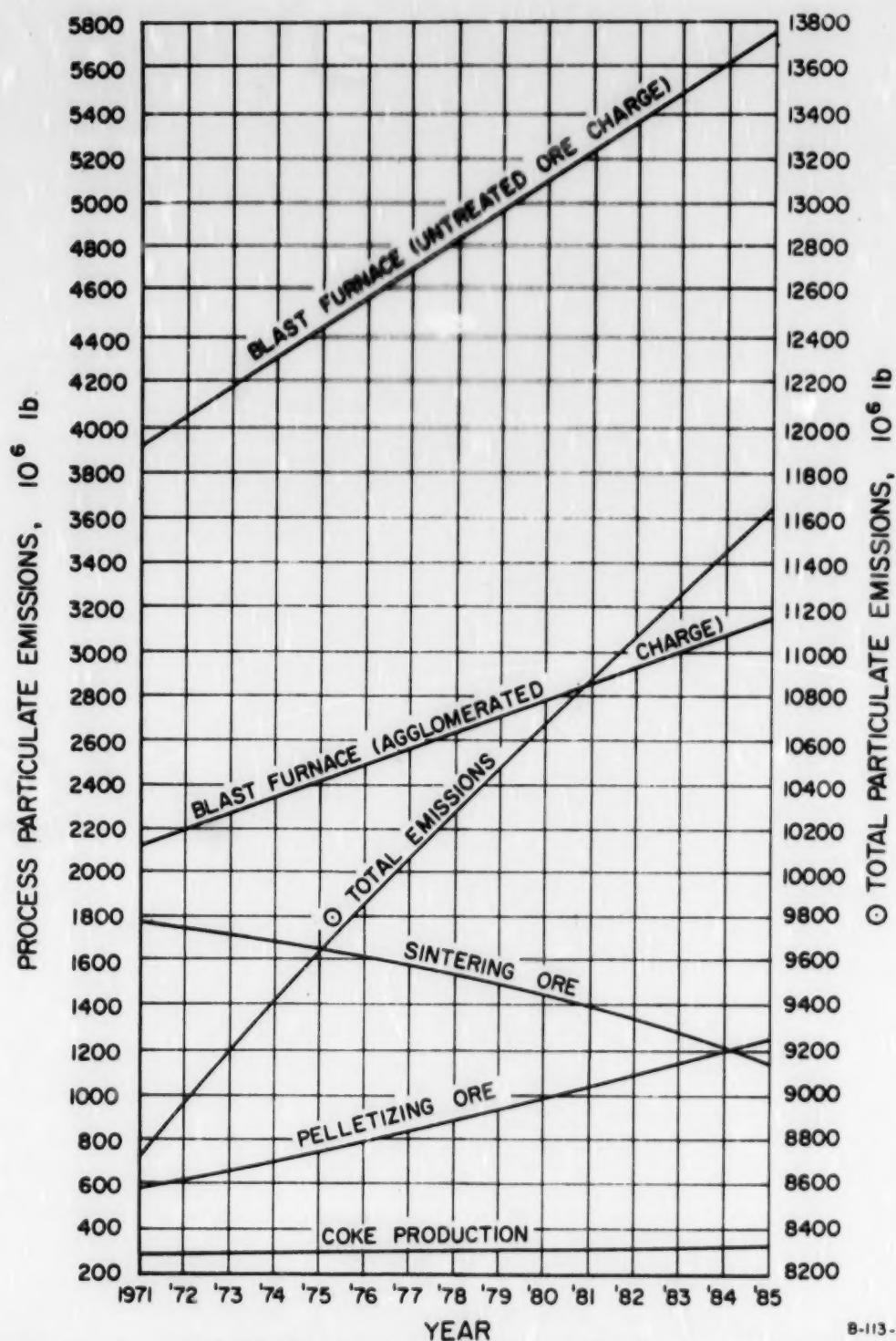
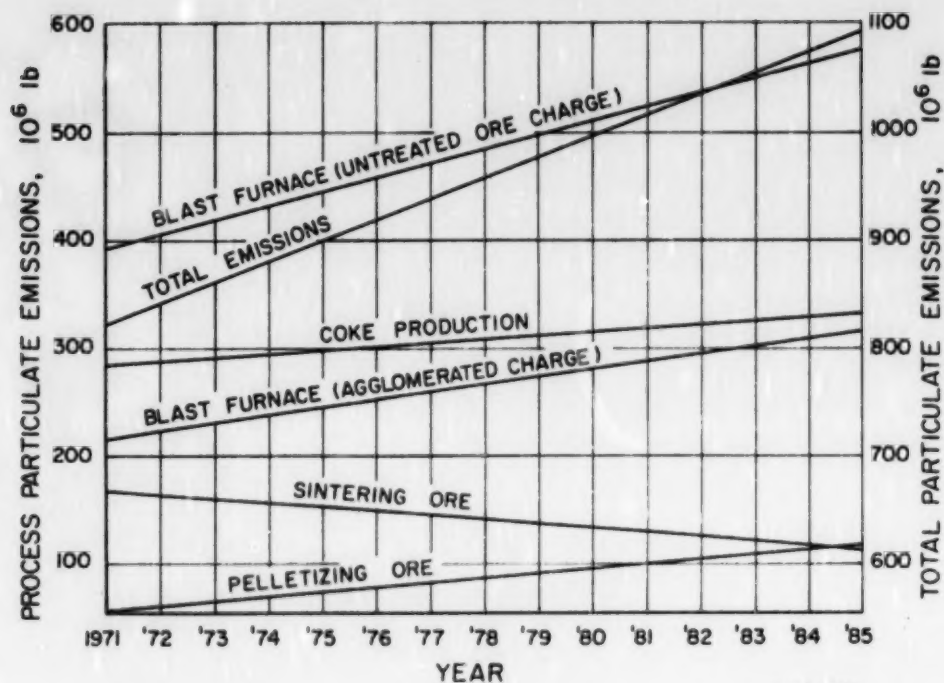


Figure 51. PROJECTED EMISSIONS OF PARTICULATES FROM THE IRON AND STEEL INDUSTRY WITHOUT CLEANUP CONTROLS



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Figure 52. PROJECTED EMISSIONS OF PARTICULATES FROM THE IRON AND STEEL INDUSTRY WITH CLEANUP CONTROLS

electric-arc furnaces. The literature indicates that the particulate emission rate for open-hearth furnaces is 22 lb/ton of steel when oxygen lances are used and 12 lb/ton when oxygen is not used. Data were not available on the exact quantity of open-hearth steel produced by using oxygen lances, but this technique usually is employed only after the furnace begins to lose capacity due to age. Thus, we assumed that oxygen is used for more than one-half of the furnace campaign, or that 50% of all open-hearth steel is produced by using oxygen lancing. Oxygen lancing also is used with the electric-arc furnace, and it affects the particulate emission rate. Again, we assumed that 50% of all electric-arc steel is produced by using oxygen.

Figure 52 shows the projected emissions of particulates when stack cleanup controls are used. These data were calculated from the data of Figure 51 by assuming cleanup efficiencies of 91% for ore preparation, 90% for blast-furnace operations, and 90% for steelmaking operations.

Particulates also are released from the steel industry boilers that produce the steam and electric power used in each of the above processes. The amount of particulates depends upon the relative use of natural gas, in-plant gases, and coal in the boilers. Earlier in this analysis, the relative usage of fuels was considered (and presented in Figures 46, 47, and 48). The only significant quantity of particulates is produced by coal burning (Figure 46), which was assumed to typically produce 240 pounds of particulates per ton of coal burned, or 9.5 pounds of particulates per million Btu of coal, assuming a 15% fly-ash content of coal. Figure 53 shows the projected emissions from coal-fired boilers. Particulate emissions from boilers operated by electric utility companies that sell electric power to the steel industry were not considered.

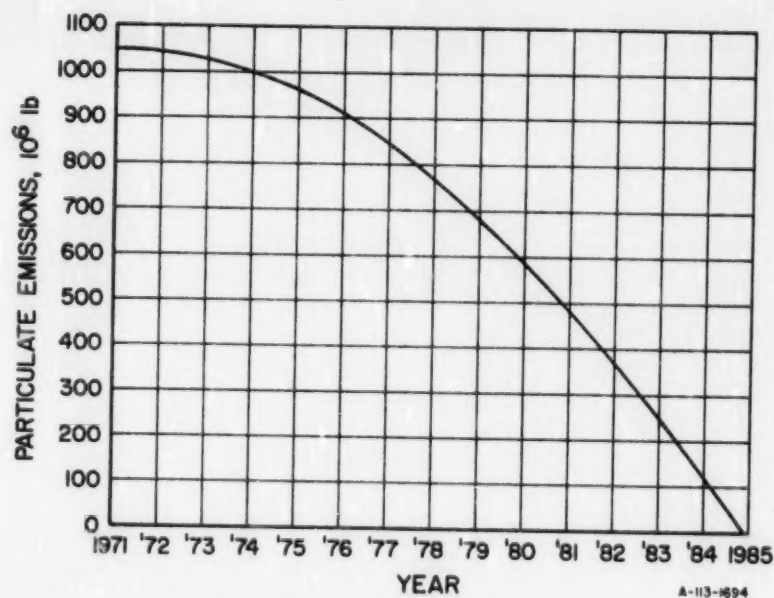


Figure 53. PARTICULATE EMISSIONS FROM BOILERS

Carbon Monoxide Emissions

The emission of carbon monoxide from the various steel processes is a function of both process materials and combustion of fuels. The major sources of carbon monoxide emissions are the sintering process, the blast furnace, the coking ovens, and the BOF process. Earlier in this report, we indicated that carbon monoxide emissions from the blast

furnace were 1750 lb/ton of iron produced. However, most of this pollutant is reclaimed as blast-furnace gas. The literature reports that only about 1% of the carbon monoxide escapes, or about 17.5 lb/ton of pig iron. Other fuel utilization areas that emit carbon monoxide but are not reported elsewhere are the pelletizing operation, blast-air stoves, and general steel-processing furnaces, such as soaking pits. The literature does not report carbon monoxide data for these systems because they are generally minor. However, for this analysis, we assumed an average emission rate of 0.0774 lb/million Btu consumed. This level of emissions is typical of hot-air generators and reverberatory furnaces when operated properly.

Figure 54 shows the total carbon monoxide emission rate projected to 1985, and Figures 55 and 56 show the projected emission rates by process. These data were calculated from the emission levels reported in Table 11 and the production and energy consumption projections presented earlier.

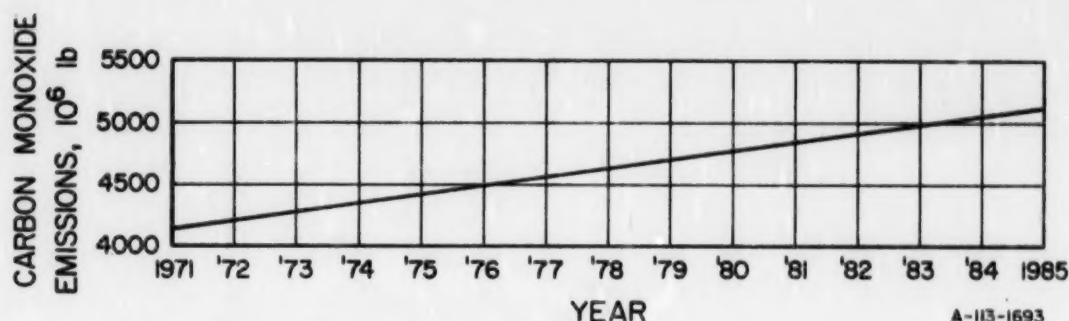


Figure 54. TOTAL CARBON MONOXIDE EMISSIONS
FROM IRON- AND STEELMAKING PROCESSES

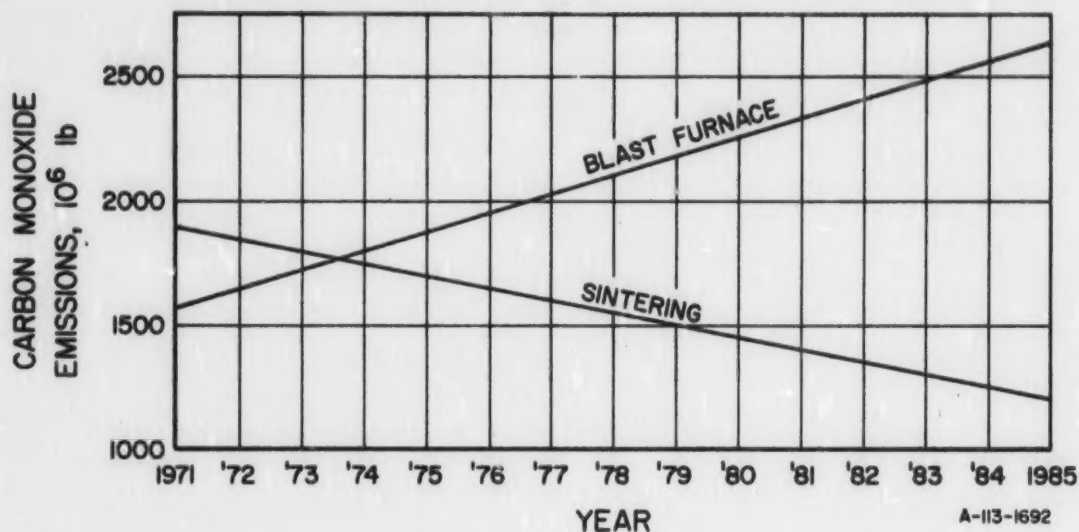
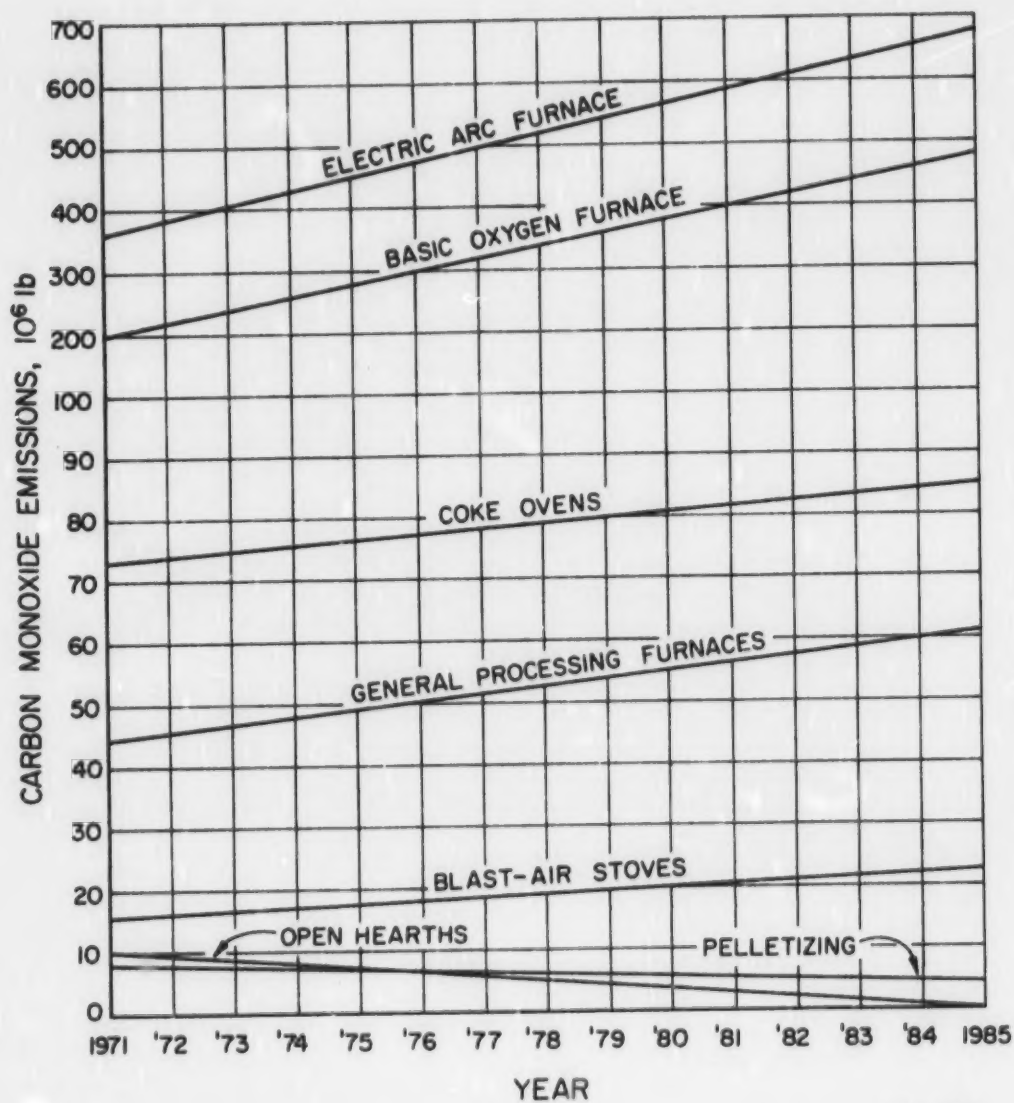


Figure 55. CARBON MONOXIDE EMISSIONS FROM IRON- AND STEELMAKING PROCESSES

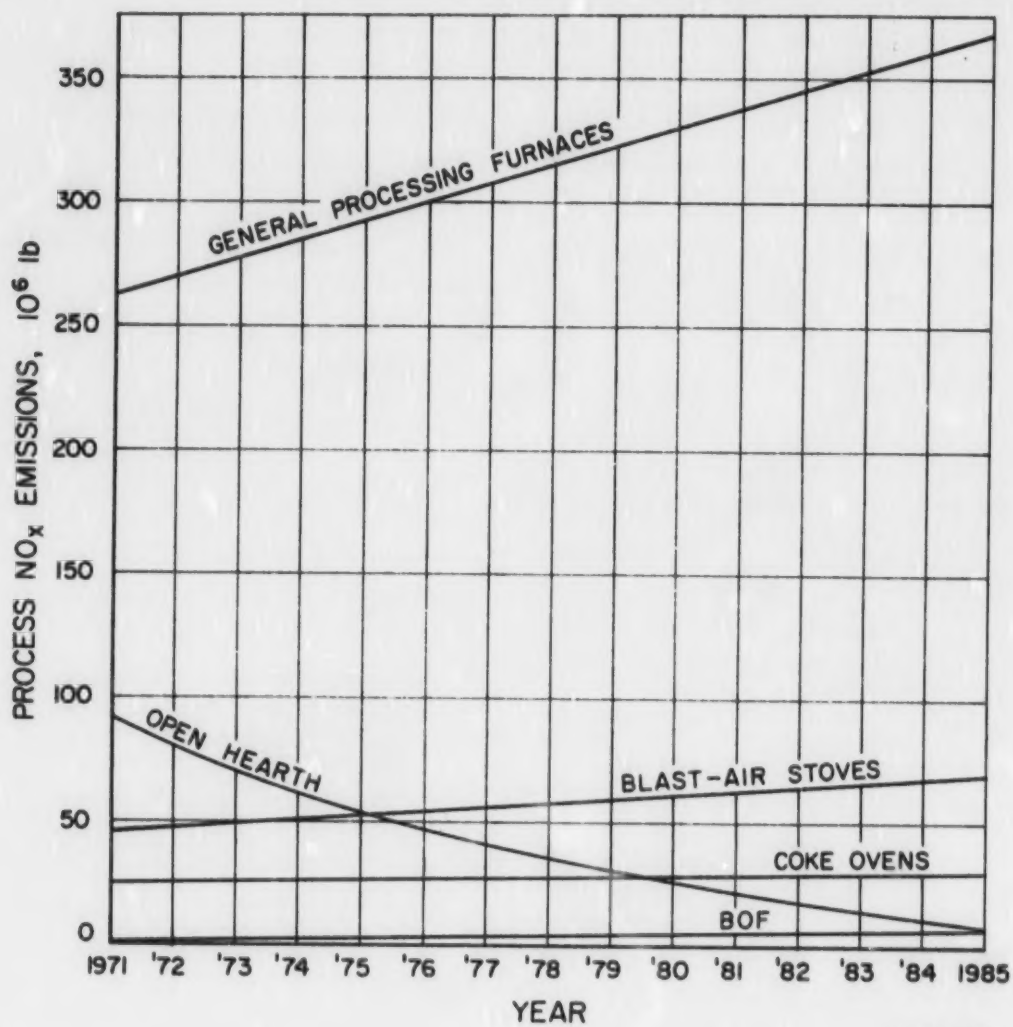
Table 11. TYPICAL CARBON MONOXIDE EMISSION LEVELS

Process	Rate of Emission
Sintering	44 lb CO/ton of sinter
Pelletizing	0.0774 lb CO/million Btu
Blast Furnace	17.5 lb CO/ton of pig iron
Coke Ovens	1.3 lb CO/ton of pig iron
Blast-Air Stoves	0.0774 lb CO/million Btu
Open-Hearth Furnace	0.0774 lb CO/million Btu
Basic Oxygen Furnace	3 lb CO/ton of steel
Electric-Arc Furnace	18 lb CO/ton of steel
General Processing Furnaces	0.0774 lb CO/million Btu



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Figure 56. CARBON MONOXIDE EMISSIONS FROM IRON- AND STEELMAKING PROCESSES



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Figure 57. PROJECTED NO_x EMISSIONS FOR IRON- AND STEELMAKING PROCESSES

NO_x Emissions

Very little information is published in the literature on the emissions of NO_x from steel processes. References on this pollutant lead the reader to believe that very little has been done to measure emission rates. We were able to determine emission rates for the coking operation and open-hearth furnace only. The coking operation typically produces 0.04 lb/ton of coal charged. The open hearth produces typically 0.70 lb/ton of steel produced. However, the NO_x emissions of many of the other processes can be estimated based on the temperature, combustion characteristics, and type of fuel used. For example, blast-air stoves use primarily in-plant gases, which have a low combustion intensity (generally low NO_x), and operate in the temperature range of 2500⁰-2800⁰F (generally intermediate NO_x levels). Data from similar heating systems show NO_x levels in the range of 200-400 ppm. This type of analysis was applied to other steel processes, with the result given in Table 12.

Table 12. TYPICAL NO_x EMISSION LEVELS

Sintering (100 ppm)	
Pelletizing (600-800 ppm)	
Blast Furnace	Unknown
Coke Ovens (200 ppm)	0.04 lb/ton coal
Blast-Air Stoves (300 ppm)	0.23 lb/million Btu
Open-Hearth Furnace	0.70 lb/million Btu
Basic Oxygen Furnace	0.23 lb/million Btu
Electric-Arc Furnace	Unknown
General Processing Furnaces	0.46 lb/million Btu

Based on the above information and the energy consumption and production rates published earlier in this report, projections of NO_x emissions were calculated and are shown in Figure 57.

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X. SIC CODE 3331 - PRIMARY COPPER

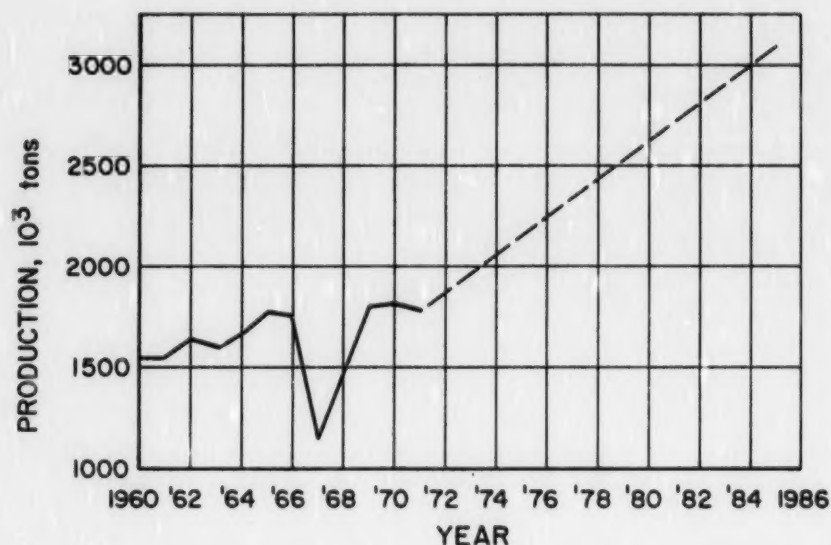
The primary nonferrous metals industry consumes approximately 3.5% of the total energy consumed by industry annually in the U.S. The study is being limited to the copper, lead, zinc, and aluminum industries* because these industries consume approximately 95% of the total energy consumed by the primary nonferrous metals industry as a whole. Based on the typical energy consumption per ton of metal produced for these primary nonferrous metals, an estimated 516 trillion Btu of energy was consumed in 1971.

SIC Code 3331 pertains to companies that are involved in the smelting of copper from raw ore and in the refining of copper by electrolytic or other processes. This classification does not include companies that engage in secondary smelting, that is, the smelting of scrap and recycled copper, nor does it include companies that engage in the rolling, drawing, or extruding of copper.

During the 1960's, growth of the primary copper industry was minimal; the annual growth rate was only 1.2% (Figure 1). Production in 1960 was about 1,550,000 tons, increasing to 1,775,000 tons in 1971.³ In spite of this low growth rate, annual production is expected to increase to 3,250,000 tons by 1985.

Energy consumption by primary copper smelters and refiners in 1971 was 71.4 trillion Btu. At current operating efficiencies, annual energy consumption will be approximately 130 trillion Btu by 1985, an increase of more than 80% over 1971. However, the potential for reducing energy consumption is very good. Two new processes that have been developed for copper production claim a 66% reduction in the energy required to produce a ton of copper concentrates.

* Sections XI, XII, and XIII discuss SIC Codes 3332, 3333, and 3334, the lead, zinc, and aluminum industries, respectively.



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Figure 1. ANNUAL COPPER PRODUCTION
(Projected After 1972)

One significant factor in the growth of the copper industry will be its ability to control sulfur oxides (SO_x) emissions from the smelters. The most reasonable solution to this problem is the conversion of the SO_x in the flue gases to sulfuric acid or sulfur, which then can be sold commercially. However, the success of this approach is limited by the concentration of SO_x in the flue gases, which, in turn, affects the economics.

Primary Copper-Manufacturing Processes

Primary copper production comprises a chain of processes in which the raw material is concentrated progressively to a high-purity final product. Figure 2 is a process flow sheet for primary copper production. Typical energy consumption figures for each process also are presented. About 80% of the world's primary copper is produced by these well-established concentrating, smelting, and converting techniques.⁸ Although this percentage is likely to decrease, these processes probably will continue to dominate in the future.

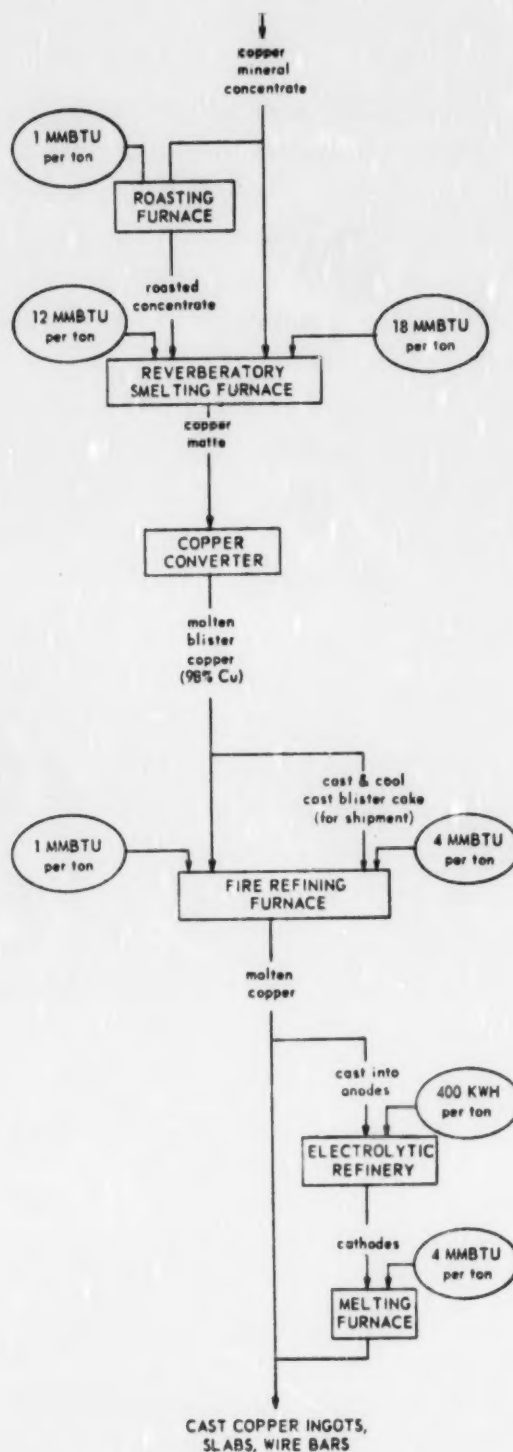


Figure 2. FLOW DIAGRAM FOR PRIMARY COPPER PRODUCTION (Source: Ref. 1)

Concentration

Because of the diminishing availability of rich ores, most of the copper-bearing materials, primarily low-grade sulfide ores, must be concentrated to make recovery of the copper profitable. Thus, the introduction of the froth flotation process in the 1920's made practical the treatment of vast deposits of low-grade sulfide ore. This process is the most important means of concentrating the copper in ore and is not likely to change in the near future. Concentrators built during the next decade will not differ very much from those operating now. Because much of the ore being processed contains only 2-3% copper, it would be very uneconomical to ship the ore in this condition. Thus, initial concentrating usually is carried out at the mines. Typically, the end product of froth flotation is 25% copper. No significant amount of energy is consumed by this process.

Roasting

Roasting, done in the copper plant, is the next step in the concentration of the ore. The purpose is to remove some of the sulfur and iron in the ore by heating the ore to the temperature necessary for the oxygen in the air to react, forming gaseous sulfur oxides and solid metal oxides. Because iron oxide is formed preferentially to copper oxide, the copper remains as copper sulfide ore, to be converted in a later step. Roasting is an autogenously heated process, consuming 1.0 million Btu of energy per ton of copper for startup.

Roasting is used optionally to treat ores that are too high in iron and sulfur concentrations. Consequently, the energy consumed by this process nationwide cannot readily be determined. However, if roasting were universally applied, the annual energy consumption would have been about 1.80 trillion Btu in 1971, or about 3% of the total energy consumed by the copper industry.

Smelting

Copper smelting has changed little during the last century; it is still basically matte (a type of copper concentrate) smelting. The changes that have occurred include the use of different sources of matte from the blast furnace to the reverberatory furnace because of changes in smelter feed and the replacement of one type of converter by another.⁴

In the typical smelting operation, the copper concentrate as received from the mine or after roasting is charged into a reverberatory furnace. Siliceous fluxes are added, and the charge is melted at 2500°F to form a copper matte (molten copper sulfide) and an iron silicate slag. The copper matte is periodically tapped from the furnace and transferred to the converter, where in a two-stage operation it is oxidized with air.¹⁰ Molten converter slag, produced in the subsequent converting operation, is recycled back to the reverberatory furnace as well. When charged into the furnace, it mixes and interacts with the bath, resulting in the recovery of a large part of its high copper content. The reverberatory slag is tapped from the furnace periodically for disposal.

The energy requirement for smelting varies considerably depending on a number of factors, including furnace design, operating practice, moisture content, and flux additions. The most important factor is feed grade, that is, the percent copper in the concentrate. Energy consumption varies from approximately 60 million Btu/ton of copper using a 10% concentrate feed to 15 million Btu/ton for a 40% concentrate, based on a fuel requirement of 6 million Btu to smelt a ton of feed.⁴ On this basis, a reasonable average figure for energy consumed is about 18 million Btu/ton of copper. The majority (90%) of the fuel consumed by this process is natural gas; the remaining 10% is fuel oil.

Converting

The copper matte product of the reverberatory furnace is reacted in a two-stage process in oxidizing converters to produce blister copper with a 98% copper content. In the first stage, iron sulfide in the matte is oxidized, and the resulting iron oxide is combined with silica flux to form an iron silicate slag. This slag then is skimmed and recycled back to the reverberatory furnace. The second-stage conversion is the oxidation of copper sulfide to metallic copper. The two-stage process is imposed by the thermodynamic requirement that most of the iron sulfide

be oxidized before the metallic copper can be produced. No fossil-fuel energy is consumed directly by this process. Oxidation is promoted by the blowing of air or oxygen-enriched air through the matte at the temperature of the matte as received from the reverberatory furnace.

Refining

Blister copper is refined in furnaces heated with natural gas. These furnaces consume about 1.0 million Btu/ton with molten blister copper and 4.0 million Btu/ton if the blister is cold and must be remelted. The bulk of the copper is refined electrolytically. The copper cathodes, or product pigs, from the fire refinery are later remelted and cast into forms suitable for metalworking operations. The melting process requires about 4.0 million Btu/ton of metal. The primary fuel used in the melting process is natural gas.

Energy Utilization Pattern

The above analysis of the production of primary copper indicates that approximately 23.0 million Btu is consumed in producing 1 ton of copper. However, the 1972 Census of Manufactures cites annual energy consumption as being 66.9 trillion Btu,¹¹ whereas primary copper production was 1,775,000 tons. On this basis, the average consumption of energy per ton of primary copper produced is 37.7 million Btu. This difference of 14.7 million Btu per ton of finished copper indicates that, during periods of no production, a significant amount of energy is used for such things as maintaining furnaces at temperature. Furthermore, the production of copper is not a continuous process; consequently, much energy is wasted.

New Technologies in Copper Manufacturing

In recent years, several new processes for producing copper have been proposed and are being developed: flash smelting, continuous smelting by means of the Worcra and Noranda Processes, electric furnace smelting, and various hydrometallurgical techniques as alternatives to smelting. In all these processes, the energy consumption per ton of copper produced is less than that of the processes they replace.

Noranda and Worcra Processes^{9,10}

The Noranda and Worcra Processes are alternatives to the typical reverberatory and converter smelting of copper. Both processes offer a means for continuously smelting and converting copper. In addition, both processes combine the smelting function of the reverberatory furnace and the converting function of the converter into a single furnace. The key to developing these processes was to establish conditions such that the smelting of concentrate at a high rate and the oxidation of iron sulfide to iron oxides and copper sulfide to copper could proceed simultaneously in the same furnace. Figure 3 is a cross-sectional view of the Noranda Process reactor or furnace, and Figure 4 shows two types of Worcra furnace designs.

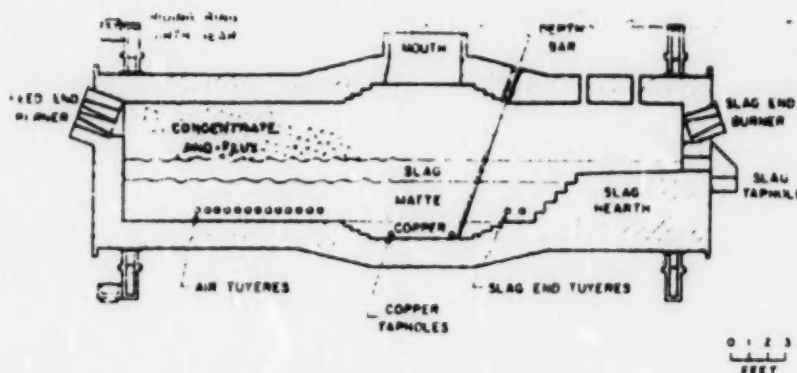


Figure 3. LONGITUDINAL CROSS SECTION OF NORANDA PROCESS PILOT PLANT REACTOR¹⁰

The reactor bath in the Noranda Process consists of slag, high-grade matte, and metallic copper layers. The copper concentrate and silica flux are distributed on the bath surface in the smelting and converting zone. This zone is strongly agitated by air or oxygen-enriched air blown through the tuyeres. Because the bath is dynamic, even in the presence of substantial quantities of iron sulfide, copper is produced and settles to the bottom of the reactor. The slag is formed by combination of the flux with the oxidized iron.

This process is very efficient in terms of heat utilization because the heat evolved by the converting reactions is used for smelting. The additional heat that may be needed is supplied by burning fossil fuels. Energy consumption by this process in a pilot-plant facility ranged from 5.5 to 6.2 million Btu/ton of copper produced,¹⁰ which is a 66% reduction in the energy consumption typical of the reverberatory furnace-converter process. For a commercial plant, the energy consumption is estimated to be even lower, approximately 3.4 million Btu/ton of copper.⁹ The proponents of the Worcra Process claim that energy consumption is even lower than for the Noranda Process, approximately 2.5 million Btu/ton of copper.⁹ The Noranda Process has been commercialized in Canada, but operating data are not yet available. An additional feature of both processes is that the off-gases contain enough sulfur dioxide to make recovery for conversion to sulfuric acid feasible.

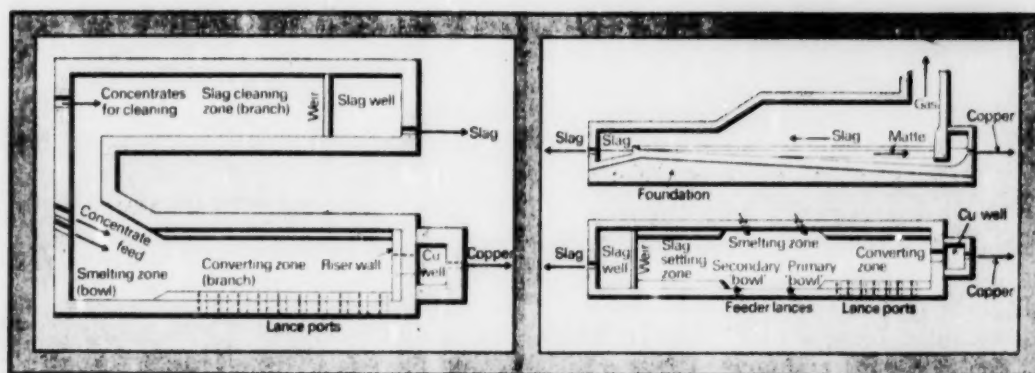


Figure 4. TWO WORCRA FURNACE DESIGNS - (Left) A PLAN VIEW OF THE U-SHAPED SEMICOMMERCIAL FURNACE AND (Right) PLAN AND ELEVATION VIEWS OF THE STRAIGHT-LINE COMMERCIAL FURNACE⁹

Flash Smelting

In the flash smelting process, oxidation reactions are carried out in a vertical shaft in a downward flowing cocurrent system. Preheated air and dried concentrate are fed in proper proportions into a burner on the top of the reaction shaft. The air and concentrate are effectively mixed in the burner, and the resulting suspension is directed vertically downward into the shaft. When the particles enter the hot shaft, ignition takes place instantaneously. By exothermic reactions, the temperature of the particles is raised to the smelting temperature. Ultimately the particles are collected in the molten bath located horizontally below the reaction

shaft. Iron oxide and silica from the feed react, forming slag, and at the same time, molten matte drops are separated and collected on the furnace hearth. The matte then is charged into a converter as in a typical smelting and converting operation.²

In general, flash smelting results in greater thermal efficiency, higher matte grade, and richer sulfur dioxide gas. The process does require a feed carrying 25% or more sulfur in order to maintain its attractiveness to the industry.³

Oxygen Enrichment

Oxygen enrichment was first used as a means of increasing smelting rates in 1952, and although the benefits appear to technically justify the process, it is not widely used. Basically the process involves the addition of raw oxygen to the combustion air of the reverberatory furnace. At one facility that installed such a system, a 25-30% increase in reverberatory furnace throughput was achieved by enriching the combustion air to 27% oxygen. Although reliable data are not available, the use of oxygen enrichment is believed to decrease energy consumption per ton of copper produced.

Hydrometallurgy

During the past 10 years, the amount of copper chemically extracted from concentrates, dumps, and on-site ores has increased considerably. However, most of these hydrometallurgical processes apply only to copper oxide ores or to ores consisting primarily of oxides with only small amounts of sulfides present. To date, no hydrometallurgical process has been successfully commercialized for the treatment of copper sulfide. Typically, the metal is leached from the ore by a solvent and then recovered from the resulting solutions in a relatively pure form. One advantage of hydrometallurgy is the elimination of the sulfur dioxide pollution problems that normally bother smelters.⁵ The capital investment is relatively low, and the processes are economical even on a small scale. Thus, such a process can be set up at the mouth of a mine to turn out refined copper instead of ore that must be shipped. In addition, the working temperatures are relatively low, and as a result, energy requirements are minimal. In spite of all its advantages, hydrometallurgy is not expected to replace any existing smelters, although it may be useful as an adjunct to smelters.⁵

Cathode Melting

Cathodes are usually melted in reverberatory, direct-arc, or shaft furnaces. Until recently, most cathodes were melted in reverberatory furnaces. One problem with the reverberatory furnace is the exposure of the copper to contamination from refractories and from sulfur in the fuel. Direct-arc melting has been going on for the last 20 years. Direct-arc furnaces are more efficient melting units than reverberatory furnaces and less prone to contamination problems. However, with the advent of the shaft furnace, even arc melting has become obsolete.⁸ The shaft furnace is the most notable development in copper refining in many years. Its primary advantage is the ability to produce a pure product. However, it requires the use of low-sulfur fuels and consistently good-quality feed.

Effect of New Technology on Energy Usage

Traditionally, about 80% of the total energy consumed by the primary copper industry has been natural gas. Thus, based on an estimated total energy consumption of 71.4 trillion Btu in 1971, approximately 57 trillion Btu of natural gas was consumed. By 1985, annual copper production is estimated to be about 3.25 million tons, and based on current levels, energy consumption will be 130 trillion Btu. However, the probable annual energy consumption in 1985 will be considerably lower than current estimates if such new technology as the Noranda or Worcra Processes gains in usage. Currently, only 16 smelters exist in the U.S. Thus, the conversion of one or two of these companies to a continuous smelting process would have a marked effect on the energy consumed by this industry. For example, if four of the 32 smelting furnaces currently in existence were replaced by the Noranda furnace and if the smelters being replaced produced 12.5% of the total annual copper production, total energy consumption by 1985 would decrease by 5%. (See Figure 5.) If one-half of the annual copper production were to occur via the Noranda Process, total energy consumption by 1985 would decrease by 18.5%. We cannot predict whether any of these furnaces will be in operation by 1985. The first production-scale Noranda furnace was scheduled for completion by early 1973 in Canada. Plans for the construction of a Noranda furnace in the U.S. have just been announced.

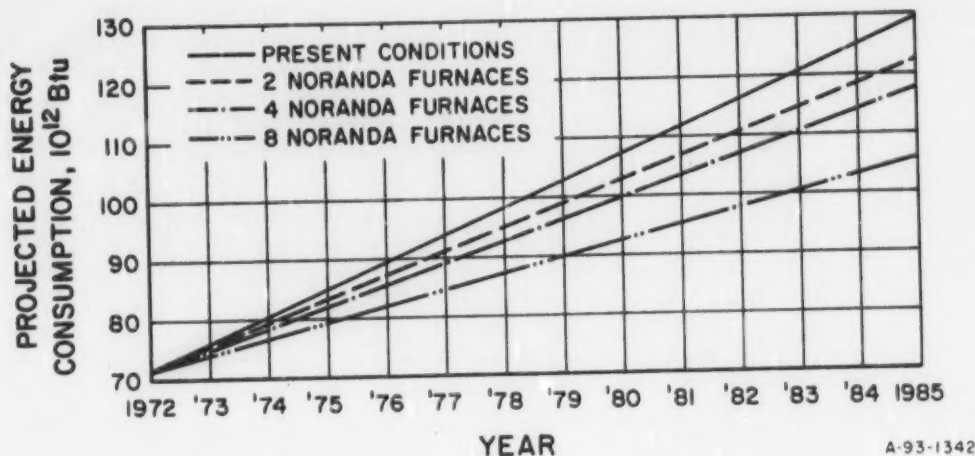


Figure 5. EFFECT OF USAGE OF NORANDA FURNACE ON PROJECTED ENERGY CONSUMPTION IN 1985

In addition, new facilities are being planned that will utilize flash smelting, electric smelting, and hydrometallurgy. However, none of these facilities are expected to be in operation before 1980 and, consequently, will not have a great impact on the industry's energy consumption pattern between now and 1985.

Air Pollutant Emissions in Copper Manufacturing

The major air pollutant emission from copper-manufacturing processes is sulfur dioxide. In 1966, according to one source, a total of 2,830,000 tons of sulfur dioxide, or about 1.6 tons per ton of copper concentrate produced, was emitted by copper producers,⁶ primarily from roasters (where used), reverberatory furnaces, and converters. On this basis, approximately 2,850,000 tons of sulfur dioxide was emitted in 1971. According to a second source, total SO_x emissions are only 1250 lb/ton of copper concentrate produced. On this basis, only 1,110,000 tons of SO_x was emitted in 1971. The breakdown of SO_x emissions by process is given in Table 1.

Present air pollution standards call for a 90% reduction in current emissions. However, the establishment of this standard appears to have been based on a study that used mathematical models. The study suggested that the combination of sulfuric acid plants and limestone slurry scrubbing could achieve this level. Copper producers contend that such reductions are not possible because a commercial limestone slurry process has not

Table 1. EMISSION FACTORS FOR PRIMARY
COPPER SMELTERS WITHOUT CONTROLS*

(Source: Ref. 12)

<u>Type of Operation</u>	<u>Particulates</u> [†]	<u>SO_x</u>
	—lb/ton—	
Roasting	45	60
Smelting (reverberatory furnace)	20	320
Converting	60	870
Refining	10	--
Total Uncontrolled	135	1250

* Emission factors expressed as units per unit weight of concentrated ore produced.

† Electrostatic precipitators reduce emissions by 99.7%.

as yet been successfully developed. Furthermore, even if the technical problems relating to limestone slurry can be solved, a new problem would be created by the amount of solid waste produced by this method of sulfur control. Copper producers contend that a 50-60% sulfur recovery is feasible.¹³

The other major air pollutant from the production of copper is particulates. Table 1 also shows the particulate emissions by process from a conventional uncontrolled copper-producing facility. The literature has reported that 99.7% of the particulates can be recovered by electrostatic precipitators.

Carbon monoxide and nitrogen oxides (NO_x) probably are also emitted by the processes for producing copper. However, no quantitative data have been reported in the literature.

Effect of New Technologies on Air Pollutant Emissions

Because SO_x emissions are of prime concern at present, the major portion of this discussion deals only with the effects of the new technologies previously discussed on sulfur dioxide emissions. The obvious solution to the sulfur dioxide emissions problem faced by the copper producers is to convert these emissions to either elemental sulfur or sulfuric acid. This conversion is technically possible and, in fact, is practiced by many of the copper producers. However, in order to make the conversion economically feasible, the percentage of sulfur dioxide in the

off-gases must be fairly high, at least 8-12%. Typically, the off-gases from reverberatory furnaces contain only 1-2% sulfur dioxide, the roaster gases (when used) contain about 7% sulfur dioxide, and the converter off-gases contain an average of 4-5% sulfur dioxide.⁷ Of these off-gases, only those from the roaster have been used successfully to produce sulfuric acid. Thus, if new technologies are to have a beneficial effect on sulfur dioxide emissions, they must ultimately produce off-gases with higher percentages of SO_x .

As previously stated, roasters, which have declined in usage over the years, are being revived. The main reasons for this revival are the interests in sulfuric acid production and in air pollution control. The new fluid-bed roasters are ideal because they operate autogenously and the off-gases contain up to about 15% sulfur dioxide.⁷ Thus, these off-gases can be readily converted to sulfuric acid.

For the smelting process, sulfur dioxide in the off-gases probably cannot be increased from the 1-2% level. However, new processes that have been developed to increase production rates and reduce fuel consumption also produce greater concentrations of sulfur dioxide in the off-gases. Flash-smelting furnaces using preheated air produce off-gases from the furnace containing 11-14% sulfur dioxide, and these gases are used successfully in manufacturing sulfuric acid. Such furnaces have been in operation in Finland and Japan for many years but are not used in the U.S.

A second method for producing high percentages of sulfur dioxide in smelting off-gases is electric smelting. The off-gases from electric smelting consist primarily of the gases generated from the charge, water vapor, and air leaking into the furnace. If air leakage is minimized, off-gas volume is minimized and sulfur dioxide concentrations in the off-gas range from 10 to 20%. At present, electric smelting is not used in the U.S. because of the availability and relative cheapness of other fuels. Also, this type of smelter eliminates the generation of dust-laden off-gases and, consequently, should decrease particulate emissions.

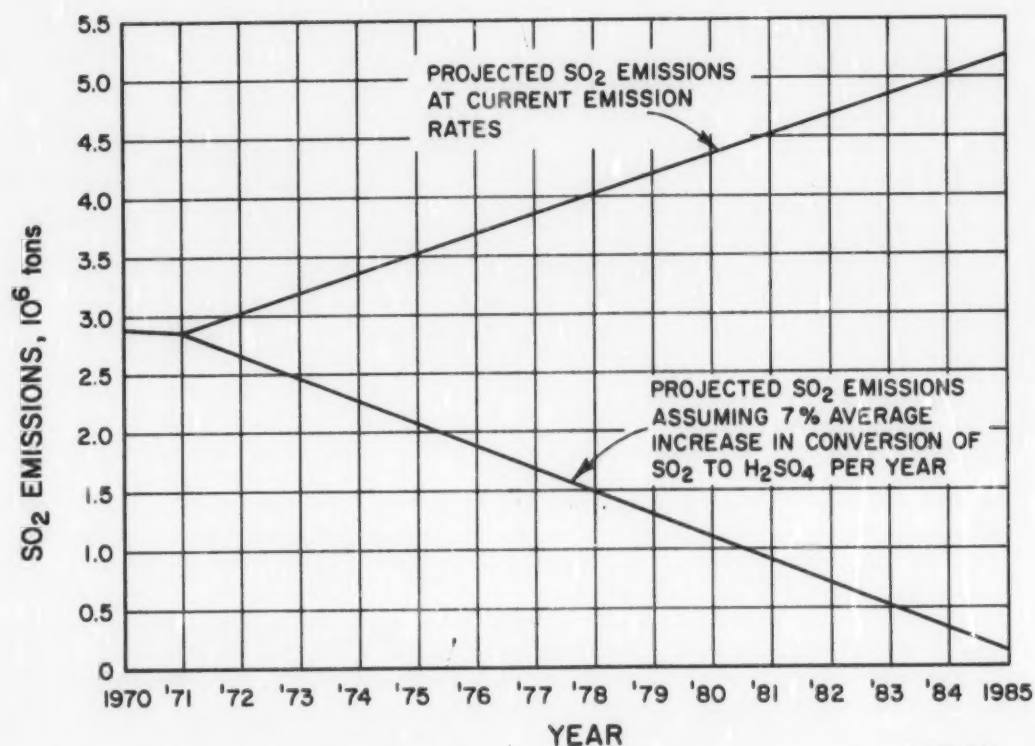
The use of oxygen-enriched air in converters was first introduced commercially in Japan; it has been in limited use in the U.S. for several years. Theoretically, the concentration of sulfur dioxide in the converter off-gases increases in proportion to the percentage of oxygen in the air used in blowing the converter. Sulfur dioxide concentrations in the off-gases of converters using oxygen-enriched air are reported to range from 10-20%. If oxygen enrichment of the blast to the converter is combined with a gas collection system comparable with that devised for the basic oxygen furnace in the steel industry, gas streams containing 15-25% sulfur dioxide or even higher concentrations should be obtained.⁷

A process for continuous smelting and converting of copper makes control of SO_x emissions easier than in the current smelting and converting processes. These continuous processes include both the Noranda and Worcra Processes. Thus far, both processes have been tested only on a pilot-plant scale. However, the Worcra Process is reported to produce a gas stream containing 9-12% sulfur dioxide. Presumably, if oxygen-enriched air is used, even higher sulfur dioxide concentrations in the off-gases seem likely. At present, no information is available on sulfur dioxide concentrations in the off-gases from the Noranda Process, but the results probably will be similar to those from the Worcra Process.

Finally, a number of processes that are being developed in the field of hydrometallurgy would permit reduction of copper while eliminating part or all of the pyrometallurgical processes that produce sulfur dioxide. One advantage of these processes is that the by-product is elemental sulfur, which is very attractive in areas where markets for sulfuric acid are limited. However, much work remains to be done on these processes.

There are several alternatives to the sulfur dioxide emission problem, and their relative attractiveness depends on several factors. Continuous smelting and converting is the most attractive solution in terms of production and pollution control. Yet, neither this process nor any of the others previously discussed will gain widespread usage by 1985, primarily for economic reasons. However, if all of the sulfur dioxide being emitted into the atmosphere by the copper industry were converted to sulfuric acid, sulfur dioxide emissions would be reduced by 99%. This estimate includes the sulfur dioxide emissions that are given off in the

production of sulfuric acid. Figure 6 shows that if the copper industry were to convert 7% of its production to processes producing high-sulfur-dioxide-containing flue gases and convert this sulfur dioxide to sulfuric acid, a 99% reduction in sulfur dioxide emissions could be achieved by 1985. However, such a conversion rate is not likely with current fuel costs, the depreciation rate of current equipment, and the capital required for conversion.



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Figure 6. PROJECTED SULFUR DIOXIDE EMISSIONS BY COPPER INDUSTRY

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XI. SIC CODE 3332 - PRIMARY LEAD

SIC Code 3332 pertains to those establishments primarily engaged in smelting lead from the ore and in refining lead by any process. Establishments engaged in the rolling, drawing, or extruding of lead are classified elsewhere.

During the 1960's, the primary lead industry was very stable, exhibiting minimal growth until 1968, when production began to increase at a record-breaking pace. By 1972, total annual production of primary lead in the U.S. had increased by nearly 50% (over 1968 production) to about 695,000 tons.¹ However, this growth rate is not expected to continue; rather, it is expected to increase as it has during the last three decades at between 1 and 2% annually.⁶ Consequently, annual production of primary lead will be about 860,000 tons by 1985, as shown in Figure 1.

Energy consumption by primary lead producers is estimated to have been 18.5 trillion Btu in 1972. By 1985, total energy consumption is expected to increase to nearly 23.0 trillion Btu, a 24% increase over 1972. These estimates are based on an average energy consumption of 26.7 million Btu/ton of primary lead produced.¹⁰ However, the newly published figures for 1972 indicate that energy consumption was only 13.3 trillion Btu,¹¹ or a unit consumption rate of about 19.2 million Btu/ton of lead produced. This indicates that a considerable improvement in the efficiency of fuel utilization has been achieved by lead producers since 1967. Further reductions in unit energy consumption are not likely by 1985.

Primary Lead-Manufacturing Processes

Primary lead production comprises a chain of processes in which the ore concentrate is beneficiated, smelted, and purified to produce 97% pure lead bullion. A schematic process flow sheet for primary lead production is presented in Figure 2.

Sintering

The first step in the manufacture of primary lead is sintering, in which the lead concentrates, lead ores, and roasted dusts from electrostatic precipitators are combined with about 1% coke fines by weight and roasted in a Dwight-Lloyd sintering machine. Sintering is a universal

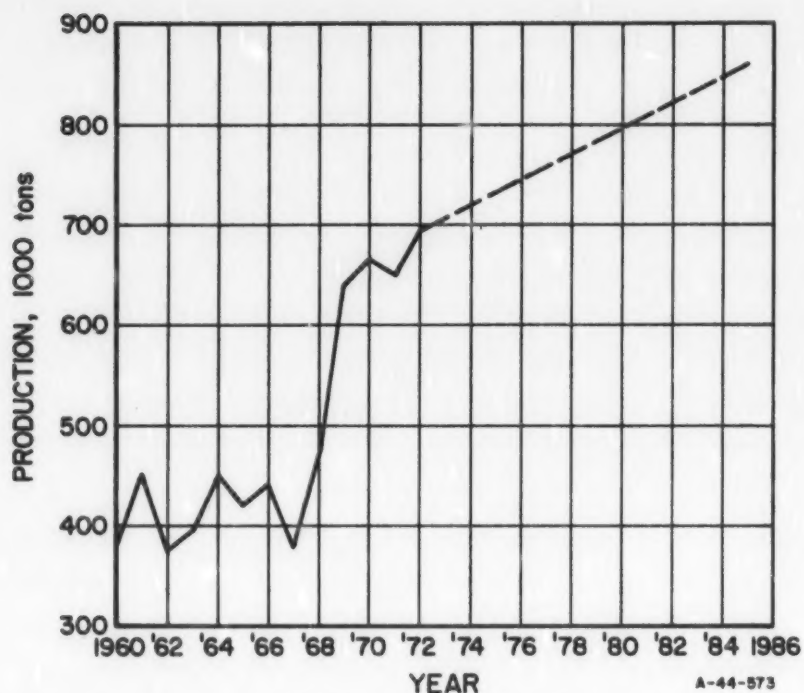


Figure 1. ANNUAL LEAD PRODUCTION

practice in the lead industry; its purpose is to remove sulfur from the ore and at the same time produce a calcine that is consolidated in a strong and porous mass suitable for reduction in a blast furnace. The main chemical reactions occurring in the process are the oxidation of lead and other metal sulfides with oxygen.

Sintering machines are continuous conveyors made of grate-bar pellets joined together. Most of the older, smaller machines are of the downdraft type, in which a sectionalized windbox underneath the conveyor is used to control the burning rates in the machine. The newer machines are of the updraft type; i. e., the wind box is located above the conveyor. Most of the machines used in the U. S. are of the updraft type.

Energy consumed in the sintering process amounts to about 2.25 million Btu/ton of lead produced, of which 40% is consumed as coke. The remaining 60% is consumed as natural gas for ignition of the sinter bed,

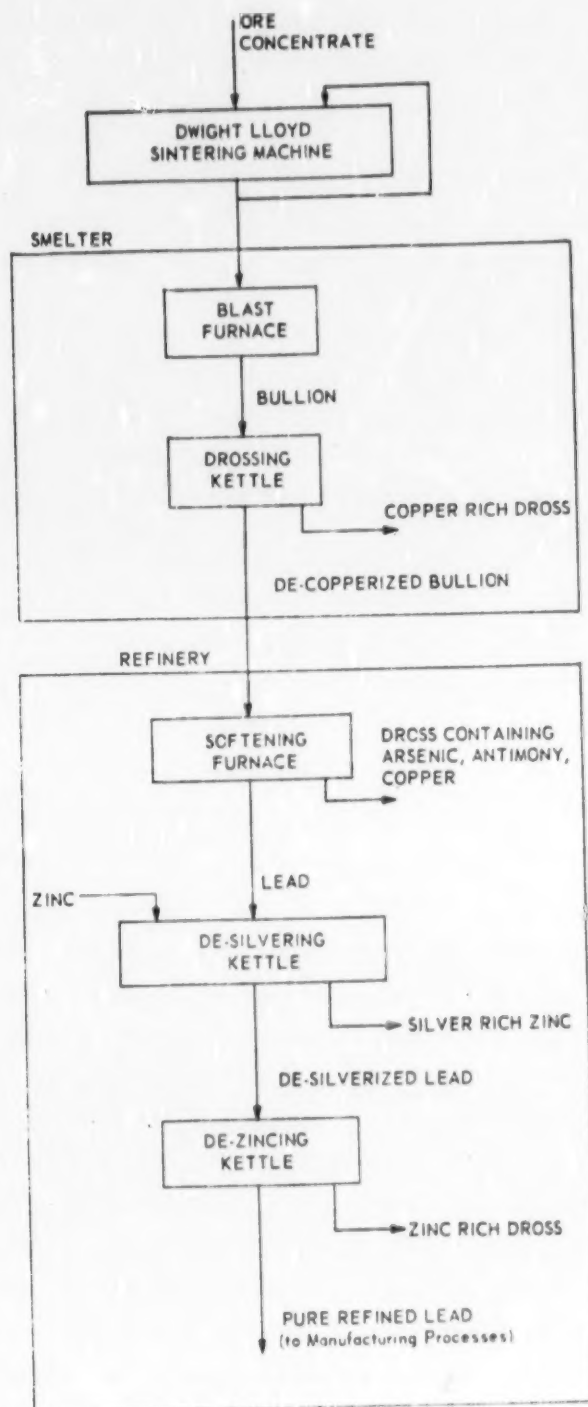


Figure 2. FLOW SHEET FOR PRIMARY AND SECONDARY LEAD PRODUCTION ²

although oil can also be used. On this basis, the sintering of lead concentrates consumed about 1.56 trillion Btu of energy in 1972.

Smelting

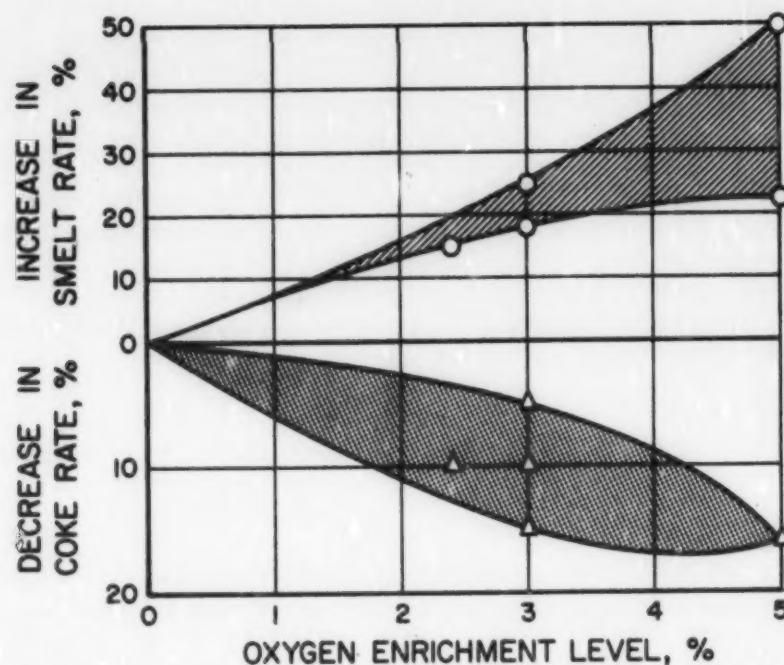
The smelting of lead is generally a two-phase operation in which the feed material, sinter, is charged into a blast furnace and the blast-furnace output is refined in dross reverberatory furnaces and lead-refining kettles.

Blast-Furnace Operation

The purpose of the blast furnace in the manufacture of lead is to reduce the lead oxide in the sinter to metallic lead. For this process, blast-furnace operation is similar to that used in the steel industry, except that furnace temperatures rarely exceed 1700°F, which is considerably lower than that used in the steel industry.

The furnace is principally a shaft furnace with water pockets for cooling. The tuyeres through which the combustion air is introduced are located near the furnace bottom. The furnace charge consists of a mixture of sinter and metallurgical coke, limestone, silica, and slag-forming materials. Coke makes up 8-15% of the charge, and sinter makes up 80-90% of the charge.⁷ The furnace uses carbon monoxide derived from the coke feed to reduce the sinter to bullion. Most of the impurities are eliminated in the slag.

The use of oxygen in the blast furnace is beginning to increase fairly rapidly. Oxygen enrichment of the blast air results in significant reductions in coke consumption and large increases in smelting rate. As early as 1949, tests were conducted with oxygen enrichment. The results of these tests showed a 10% reduction in coke consumption and a 15-20% increase in smelting rate at an oxygen enrichment level of 2.5%.³ Other studies conducted since then have shown coke consumption reductions as high as 16% and smelting rate increases as high as 53% for a 5% enrichment level. Figure 3 shows the effect of oxygen enrichment on coke rate and smelter rate as determined by a number of investigators over a period of years. However, data on the number of lead producers currently using oxygen enrichment are not available, and consequently, neither are data on average energy consumption. Without oxygen enrichment, this process consumes an estimated 7.5 million Btu/ton of lead produced.⁸ Thus, on this



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Figure 3. EFFECT OF OXYGEN ENRICHMENT OF BLAST AIR ON SMELTER RATE AND COKE RATE OF LEAD SMELTER

basis, approximately 5.2 trillion Btu of energy was consumed by this process in 1972.

Furnace products discharged from the bottom are lead metal, matte, speiss, and slag, all in liquid form. In some plants, the first three products are sent to lead refining without separation from each other. In other plants, the lead is separated and sent to refining, and the speiss and matte go to a dross furnace. Slag is removed separately and conveyed to a fuming furnace for recovery of lead and zinc. Some slag may be ground up and recycled into the sintering process for flux.

Refining

The lead-refining process in a primary lead smelter consists of a dross reverberatory furnace and several lead-refining kettles. During the course of this process, impurities such as arsenic, antimony, zinc, silver, and copper (if it has not already been separated) are removed. Assuming that the copper has already been removed, the bullion is softened in a reverberatory furnace in which the arsenic, antimony, and residual copper are

removed. In addition, small amounts of sulfur are oxidized. The lead then is transferred to a heated kettle to which zinc is added to combine with any silver that may be present in the lead. The silver-rich zinc is removed, and the desilverized lead is transferred to another heated kettle, in which the remaining zinc is oxidized and removed. The resultant product is virtually pure lead.

Typically, the refining process consumes about 5.0 million Btu/ton of lead.⁸ On this basis, about 3.5 trillion Btu of energy was consumed for refining of lead in 1972. Of this amount, approximately 90% was consumed as natural gas; the remaining 10% was fuel oil.

Energy Utilization Pattern

According to the above analysis of process energy consumption, approximately 13.25 million Btu of energy is required to manufacture 1 ton of primary lead. As in other industries, the actual energy consumed was considerably higher than the energy required. In 1972, 13.2 trillion Btu of energy was consumed in the manufacture of primary lead.¹¹ This is about 45% higher than the amount of energy that is calculated by summing typical processes consumption, which is indicative of the amount of energy that is wasted and used for miscellaneous process segments. Note however, that according to Bureau of Census statistics,^{10,11} this industry seemingly has made significant strides in a short time to eliminate the causes of inefficient fuel uses, as evidenced by the decrease in unit energy consumption to 19.2 million Btu/ton in 1972 from 26.7 million Btu/ton in 1967. Of the total amount of fuel consumed, coke, coal, and natural gas account for more than 90%.

New Technologies in Lead Manufacturing

Beginning with the initial processing of the concentrate as received by the plant, the major new technology revolves around the development of an updraft sintering machine. Updraft sintering has been known since 1898, when it was used in sinter pots. However, with the advent of continuous sintering, updraft sintering was found difficult. Consequently, the downdraft process became common practice. In the downdraft process, a draft of air is blown down through the blended charge in the sintering machine after it has been ignited on the moving grate. In the updraft process, the draft of air is blown up through the charge.

The updraft process offers several advantages over the downdraft process: higher output, less equipment wear, and lower power consumption.¹³ The reduction in power consumption is achieved by increased air output at lower pressures, resulting in a decrease in power consumption by the sinter fans. The reduction in power consumption is estimated to be about 20%. Actual consumption figures are not available. Updraft sintering offers other advantages such as greater product homogeneity and higher lead content. Such a sinter would promote the smelting operation in the blast furnace. Updraft sintering also results in increased sulfur removal, thus resulting in the production of off-gases suitable for direct conversion into sulfuric acid. In recent years, updraft sintering has begun to gain usage in the U. S. to the point that most companies currently use it.

Direct Smelting

The idea of single-step smelting has been around for many years, but it is only recently that research has made such a process feasible. Advantages of the process include the elimination of the sinter plant, a decrease in fuel consumed for heating and reduction, the elimination of the recirculation of diluent (such as blast-furnace slag), the increase of sulfur dioxides in the off-gases to make recovery as sulfuric acid economically attractive, and the use of concentrates as received without special treatment except for drying.⁵

The basic principle of the process is the oxidation of lead sulfide to form lead and sulfur dioxide. For this process, a special reaction vessel was designed. At the start of a campaign, hot refined lead is charged into the vessel. At this point, the air/gas burner is lit and the vessel rotated such that the lead covers the tuyeres. Feeding of the lead concentrates is initiated, and air is blown through the bath and concentrates by means of the tuyeres. The result is the formation of lead and slag, which are then withdrawn from the converter.

Energy requirements for this process are minimal. On a theoretical basis, the energy required by this process is 0.14 million Btu/ton of concentrates, assuming no heat losses. A more realistic estimate of energy requirements would be 0.4 million Btu/ton of concentrates, assuming no heat losses.

This process has been tested on an experimental converter, but has not been completely developed as yet. The main problem is the unusually high

refractory wear, especially in the tuyere area of the reaction vessel. Some work to develop suitable refractories is being performed; however, no solution has yet been found.

Flash Smelting⁴

The use of flash smelting of lead concentrates is relatively new, although flash smelting is used in the copper and nickel industries. (For an explanation of flash smelting, see the section entitled "Flash Smelting" under SIC Code 3331 - Copper.) Flash smelting of lead has been accomplished on a pilot-plant scale, demonstrating that lead smelting can be performed continuously without sintering. Although no operating figures are available, the indications are that total fuel consumption is relatively low. Another advantage of this process is that very high grade lead concentrates can be used without dilution by return slag. The only fluxes needed are those required to make a suitable slag composition with a gangue of the concentrate. This results in a much smaller slag fall and lower lead losses in the slag than in conventional melters.

As in flash smelting in the copper industry, thermal efficiency is increased and richer sulfur dioxide gas is given off. Thus, treatment of the sulfur dioxide in acid plants is more attractive. In spite of these advantages, flash smelting of lead is not in use in the U. S. at present.

Boliden Process³

The main production unit in the Boliden Process is an electric hearth furnace. In this process, electrical energy supplies the heat necessary to carry out the smelting of lead-rich concentrates. The only material preparation required is drying of the concentrates.

In the Boliden furnace, electrodes are submerged in a molten bed of lead and slag. High-voltage current is forced through the electrical circuit formed by the electrodes and slag. The resistance to the current flow by the slag layer provides the necessary heat of reaction.

Compared with conventional processes, the Boliden process offers the advantages of low capital cost, avoidance of metallurgical coke, recovery of waste heat in the form of steam, and production of a gas rich enough in sulfur dioxide to make sulfuric acid production feasible. Reportedly, energy consumed in this process is about 2.75 million Btu/ton of lead refined.

If fossil fuel consumption for generation of the electricity is considered, total energy consumption is about 9.2 million Btu/ton of lead refined.

Hydrometallurgy

As in the copper industry, hydrometallurgical processes for lead concentrating and refining have been developed. However, no commercial plants exist nor are any expected to be built, at least until the design and construction problems surrounding the leaching step are solved. In addition, recovery and separation of minor components are anticipated to be more difficult than in pyrometallurgical processes. In spite of the existing problems, there is no doubt that commercialization will eventually occur because the incentives in terms of reduced energy utilization and air pollutant emissions are strong.

Effect of New Technologies on Energy Utilization Pattern

In spite of the availability of new processes for lead manufacturing, no significant changes are expected in the foreseeable future. Consequently, the pattern of energy utilization is not likely to change either. However, at present, either the Boliden process or a direct smelting process would be acceptable to the industry if a change were to be made. From the industry's point of view, widespread usage of either process would result in considerable reductions in energy consumption. Figure 4, for example, shows the potential effect of a direct smelting process on total energy consumption as a function of the utilization of such a process by the industry and compares this projected energy consumption with the projected annual consumption in 1985. The Boliden process also would result in significant reductions in energy consumption from the industry's point of view if it were to be widely accepted. However, if the energy consumed for electricity generation also is considered, the reduction in energy consumption from current practice would be insignificant.

Air Pollutant Emissions From Lead-Manufacturing Processes

The primary air pollutant emissions from lead-manufacturing processes are sulfur dioxide and particulates. In 1966, an estimated 146,000 tons of sulfur dioxide was emitted by lead producers, or 0.33 ton/ton of lead produced. On this basis, an estimated 229,000 tons was emitted in 1972. These data are in good agreement with emission data previously published by the EPA (Table 1).

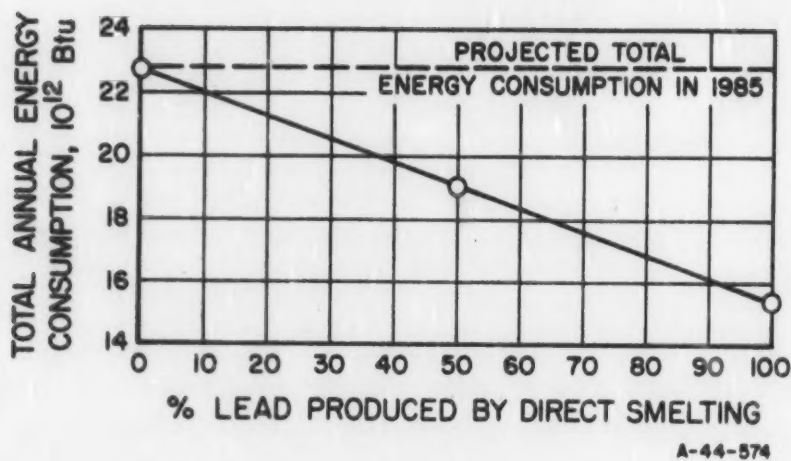


Figure 4. EFFECT OF UTILIZATION OF DIRECT SMELTING ON TOTAL ENERGY CONSUMPTION

Table 1. AIR POLLUTANT EMISSION FACTORS FROM PRIMARY LEAD SMELTERS¹²

Process	Particulates ^a	Sulfur Oxides
	lb/ton ^b	
Sintering and Sinter Crushing	50 ^c	660
Blast Furnace	75	d
Reverberatory Furnace	12	d

^a Electrostatic precipitators collection efficiency, 96%; baghouse collection efficiency, 99%.

^b Emission factors expressed as units per unit weight of concentrated ore produced.

^c Pounds per ton of sinter.

^d Overall plant emissions for SO_x, 660 lb/ton of ore produced.

The main source of sulfur dioxide emissions is the sulfur in the raw ore. Compared with that in copper and zinc ores, the concentration of sulfur in lead ore is relatively low, about 0.155 lb/lb of metal.⁶ The primary method of control, as in the copper industry, is the recovery and conversion of the sulfur dioxide to sulfuric acid. To make this conversion feasible, concentrations of 6-7% sulfur dioxide in the effluent gases are required. Typically, the sintering operation is the major source of sulfur dioxide emissions. In this process, 85% of the total sulfur is eliminated from the feed as sulfur dioxide. Off-gases from a smelter using updraft sintering machines can contain 4-6% sulfur dioxide. However, flue gas recirculation is required to achieve these concentrations because most machines currently in use have large air leaks that dilute the sulfur dioxide to concentrations of 1-3%.

The lead blast furnace is a relatively minor, but quite variable, source of SO_x emissions. Concentrations from 0.005 to 0.018% have been reported on one furnace, whereas concentrations as high as 6.05% have been reported on others.⁹ In general, SO_x emissions from the blast furnace vary in accordance with the percentage of sulfur in the feed, which is usually less than 15% of the sulfur originally in the ore. The SO_x emissions from refining operations are negligible.

The sintering operation and the lead blast furnace are the primary sources of particulate emissions, as shown in Table 2. Particulates from the sintering operation are primarily lead, zinc, and sulfur. Particulates emitted from the blast furnace are a combination of sulfates, oxides, lead sulfide, and coke dust.⁶ Particulates from the sintering operation are recovered from the effluent gas stream by settling in large flues and by electrostatic precipitators and baghouse filters (Table 3). Collection efficiencies are up to 96% for precipitators and 99.5% for baghouses.

After cooling, the blast-furnace effluent is cleaned in baghouses by using wool or fiber-glass bags. The collected dust usually contains a high concentration of lead as well as quantities of cadmium and arsenic. Consequently, the collected dust usually is recycled to the sintering machine.

Table 2. PARTICULATE EMISSIONS FROM
LEAD-MANUFACTURING PROCESSES⁶

<u>Process</u>	<u>Emission Factor</u>	<u>Collection Efficiency</u>	<u>Emissions, tons/yr</u>
Ore Crushing	2 lb/ton ore	0.0	6,950
Sintering	520 lb/ton lead	0.86	25,298
Blast Furnace	250 lb/ton lead	0.83	14,769
Drossing Kettle	--		
Softening Furnace	--		
Desilvering Kettles	--		
Cupeling Furnaces	--		
Refining Kettles	--		
Dross Reverberatory Furnace	--		
	20 lb/ton lead	0.50	3,475
Materials Handling	5 lb/ton lead	0.32	1,182
Total			51,674

Table 3. LEAD SMELTER CONTROL EQUIPMENT⁶

<u>Process</u>	<u>Control Device</u>		<u>Efficiency</u>	
	<u>Primary</u>	<u>Secondary</u>	<u>Primary</u>	<u>Secondary</u>
Sinter Machine	Centrifugal	Electrostatic precipitator, bag filter	80-90	95-99
Blast Furnace	Centrifugal	Electrostatic precipitator	80-90	95-99
Reverberatory Furnace	Waste-heat boilers, tubular coolers	Electrostatic precipitator, bag filter	70-80	95-99

Effect of New Technology on Air Pollutant Emissions

Sulfur dioxide emissions will reach an estimated 284,000 tons/yr by 1985 if current emission rates continue unchecked. However, conversion of these emissions to sulfuric acid would reduce this figure by 99% to a mere 2840 tons/yr including sulfur dioxide emissions from the acid plant itself. However, the emission levels required to meet this figure are not expected to be reached in the foreseeable future.

In the more distant future, the development and satisfactory commercialization of the direct smelting of lead sulfide concentrates will drastically reduce sulfur dioxide emissions. Such a process would eliminate the roasting and sintering process, the major source of sulfur dioxide. Other new processes include converting the concentrates to metal by air blowing, which produces off-gases containing 13-14% sulfur dioxide; flash smelting, which produces off-gases containing 10-12% sulfur dioxide; and the Boliden process for direct smelting of concentrates in an electric furnace, which produces off-gases containing 6% sulfur dioxide. In all these processes, the gases would be fed into an acid-manufacturing process. As previously stated, none of these new technologies is likely to be in widespread usage before the year 2000; thus, their contribution to air pollutant emissions reduction in the interim should be minimal.

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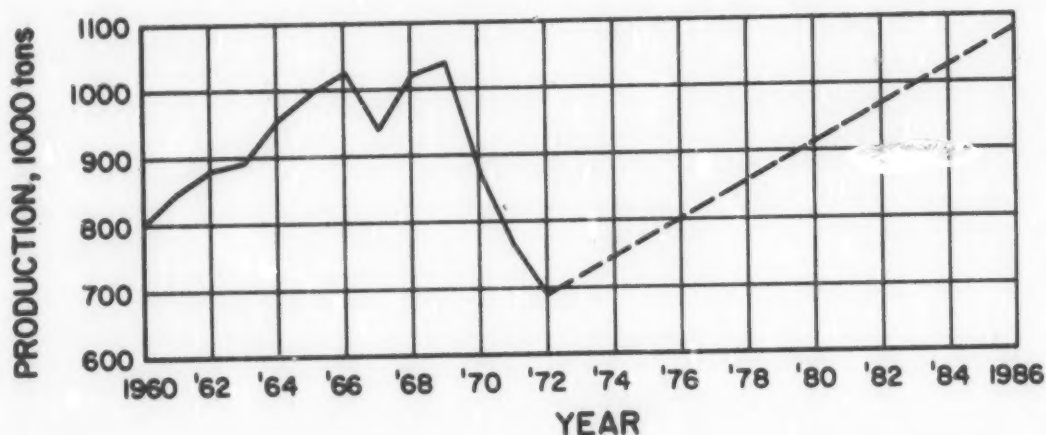
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XII. SIC CODE 3333 - PRIMARY ZINC

SIC Code 3333 pertains to those establishments engaged in smelting zinc from ore and in refining zinc by any process. This classification does not include establishments engaged in secondary smelting, nor does it include establishments engaged in the rolling, drawing, or extruding of zinc.

Prior to 1969, the zinc industry exhibited a moderate growth rate of about 4% annually. However, after 1969, production declined sharply because of the closing of seven smelters that accounted for about 30% of the 1969 U.S. smelter capacity.¹ (See Figure 1.)



A-44-569

Figure 1. ANNUAL PRIMARY ZINC PRODUCTION
WITH PROJECTION TO 1985

Most of these smelters were shut down because of outmoded equipment and operations, in addition to the burden of environmental cleanup. An additional 20% of the 1969 smelter capacity is currently in jeopardy of being shut down for the same reasons. In spite of these setbacks, the future of the industry is bright, as the domestic demand for zinc is expected to increase at the rate of about 3.5% annually. This increase in demand will help support the domestic price of zinc and thus tend to motivate new entries into the industry. Consequently, by 1985, domestic production of primary zinc slabs should approach 1.050 million tons/yr, a 53% increase over 1972 production.

Energy consumption by primary zinc smelters and refiners is estimated to have been about 38.0 trillion Btu in 1972. This is based on an average unit energy consumption rate of 55.2 million Btu/ton of zinc produced.¹² In spite of the expressed optimism about the future of the industry, zinc technology is not expected to offer any significant improvements in production practices. As a result, the unit energy consumption rate is not likely to change from current practice. However, the figure for the energy required to produce 1 ton of zinc given above is an average figure representing four current major zinc-smelting processes that have widely varying energy requirements. Two of these processes are expected to disappear altogether, and utilization of the two remaining processes, being more efficient from an energy standpoint, should result in a decrease in average unit energy and consumption and pollutant emission.

Primary Zinc-Manufacturing Processes

Four major extraction processes are available for producing zinc, all of which are currently used in the U.S: the horizontal retort, the vertical retort, the electrothermic process — all of which are pyrometallurgical — and the electrolytic process, which is hydrometallurgical. Up to a point, all four systems contain three similar processing steps: 1) the initial sulfur removal is carried out in roasters, 2) further impurities are removed by sintering in the pyrometallurgical methods and by leaching in the electrolytic process, and 3) the prepared zinc-bearing material is fed to final, and divergent, metal-producing units for which slab processes are named. (See Figure 2.)

Ore Concentrate Preparation

Prior to the extraction of zinc, the ore concentrates are prepared by any of several different combinations of processes. The choice of method depends on the physical and chemical properties of the raw material and on the extraction process that is to be used. Zinc extraction requires that the raw material, primarily zinc sulfide, first be processed to convert the zinc to zinc oxide. This conversion is accomplished by roasting, sintering, and/or calcining operations. Some plants both roast and sinter the zinc sulfide concentrates before extraction, whereas other plants use only sinter machines. The latter plants, in effect, are roasting and

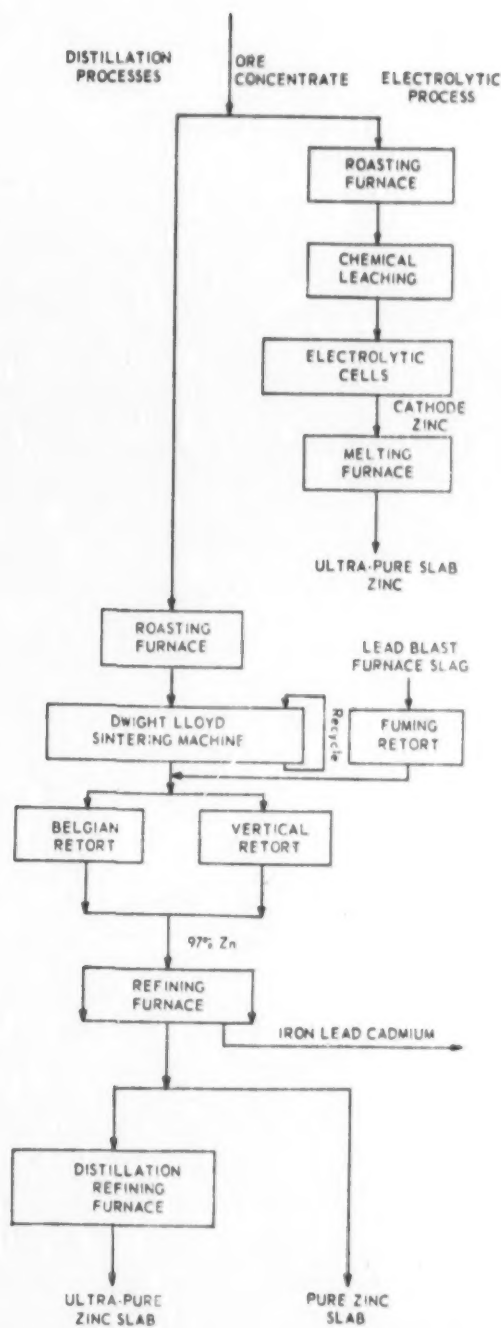


Figure 2. FLOW SHEET FOR PRIMARY AND SECONDARY SLAB ZINC PRODUCTION²

sintering in one step. Calcining is performed only on oxide ores or on material that has previously been oxidized by roasting.

Roasting and Sintering

The first step in the preparation of the zinc sulfide ore is the roasting operation, in which the ore is mixed with coke and heated autogenously. Operating conditions for roasting vary from plant to plant according to the composition of the raw material and the specific use of the roasting calcines. Table 1 summarizes typical zinc roasting operations currently being used and shows the various ranges for all the main operating parameters.

Table 1. TYPICAL ZINC ROASTING OPERATIONS³

Type of Roaster ^a	Operating Temp, °F	Feed Capacity, tons/day	Dust in Off-Gas, % of feed	Off-Gas SO ₂ , %
Multiple Hearth	1200-1350	50-120	5-15	4.5-6.5
Multiple Hearth ^b	1600-1650	250	5-15	4.5-6.5
Ropp ^c	1200	40-50	5	0.7-1.0
Fluid Bed ^d				
(Dorr-Oliver)	1640	140-225	70-80	7-8
Fluid Bed ^c				
(Dorr-Oliver)	1650	240-350	75-85	10-12
Fluid Bed				
(Lurgi)	1700	240	50	9-10
Suspension	1800	120-350	50	8-12
Fluid Column	1900	225	17-18	11-12

^a Dead roast except where otherwise noted.

^b First stage is a partial roast in multiple hearth, and second stage is a dry-feed dead roast in Dorr-Oliver fluid bed.

^c Partial roast.

^d Slurry feed.

Of the roasters listed, the Ropp hearth roaster is the oldest type still in use. It is a long, narrow, mechanically rabbled reverberatory furnace divided into two parallel hearths. Operating conditions are generally on a small scale, that is, low hearth temperatures and low feed rates. One disadvantage of this type of roaster, from a pollution point of view, is the low sulfur dioxide concentration in the off-gases.

Multiple-hearth roasters are the next oldest type currently in use. These units are 20-25 feet in diameter and have from 7 to 16 hearths; their feed capacity rates range from 100 to 250 tons/day. In this roaster, the required heat is obtained from the combustion of the sulfur with the oxygen in the air. However, when concentrations of less than 1.0% of sulfide sulfur in the calcine are required, some auxiliary fuel, about 4 million Btu/ton of feed, must be used. Because of the relatively low operating temperatures and the large volume of off-gases, waste-heat recovery is not economically practical.

The suspension, or flash, roasting process is similar to the combustion of powdered coal in furnaces, in that the finely ground particles are sprayed into the combustion chamber into a stream of combustion air. As in the multiple-hearth roasters, the sulfur content of the ore acts as the primary fuel source. Typically, a suspension roaster is a refractory-lined, cylindrical steel shell enclosing a large combustion chamber in its upper portion. The lower part contains two to four hearths. Rabble arms on a rotating shaft move the material on the hearths. The lower one or two hearths dry the ore before it is ground and sprayed into the upper combustion chamber, where calcination takes place. Process temperatures approach 1900°F, making waste heat recovery economically practical.

The fluid-bed roaster is the newest development in zinc sulfide roasting; several types exist. The primary difference among these roaster types is the method used to charge the feed. In some, a wet slurry is charged, whereas in others, a dry charge is fed to the combustion chamber. Operating temperatures range from 1625° to 1750°F, and temperature control is achieved by varying the feed rate. A newer type of fluidization roaster recently placed in operation is described as a fluid-column roaster that approaches true fluidization. This is accomplished by pelletizing and close sizing of the feed. The resulting product does not require sintering.

In all of the roasters used, combustion of sulfur in the feed is the source of heat; consequently, the process is self-sustaining. The only additional fuel required is about 1.0 million Btu/ton of ore for ignition; the primary fuel used is natural gas. As stated above, some multiple-

hearth roasters require auxiliary fuel to achieve the desired sulfur level in the calcine. Based on this information, approximately 1.0 trillion Btu of energy was consumed for roasting in 1972.

Sintering in the zinc industry is used primarily to agglomerate the roaster calcine for further processing. If the zinc is to be processed electrolytically, sintering is not used. Only if the zinc is to be processed pyrometallurgically is sintering necessary. In this event, Dwight-Lloyd sintering machines similar to those used in other nonferrous metal industries are used. Table 2 summarizes typical zinc sintering operations.

Table 2. TYPICAL ZINC SINTERING OPERATIONS³

	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3</u>
New Feed Material	Calcine	Calcine	Concentrate
Total Charge Capacity, tons/day	240-300	400-450	550-600
Machine Size, ft	3.4 X 45	6 X 97	12 X 168
Fuel Added to Feed, %	6-7	10-11	0-2
Total Sulfur in New Feed, %	8	2	31
Recycle, % of new feed	35-75	40-70	80
Dust in Off-Gas, % of feed	5	5-7	5-10
Off-Gas SO ₂ Content, %	1.5-2.0	0.1	1.7-2.4

The sintering machine comprises moving pellets upon which the feed is placed. The feed is a mixture of calcines or concentrates, recycled ground sinter, and coke or coke dust, which have been sized and pelletized. The loaded pellets move under a small gas- or oil-fired muffle where the bed is ignited. Air is forced down through the bed, resulting in rapid combustion of the ignited material and formation of a porous, relatively hard clinker. The product is discharged from the pellets as they burn over at the end of the machine for return to the feed end. Fuel consumption is estimated to be about 1.0 million Btu/ton of concentrate processed.⁸ In 1970, 57% of the zinc produced was processed pyrometallurgically; consequently, sintering was used on only 57% of the calcine and concentrates processed. On this basis, less than 0.5 trillion Btu of energy was consumed for sintering in 1972.

Calcining

Calcining is a heat-treating process that is used exclusively for oxidized materials, such as oxide ore concentrates or the product materials from the roasting of sulfide ore concentrates. Calcining is accomplished in a rotary kiln, and the product is hard, randomly sized nodules that subsequently are treated for zinc extraction. This process is not very widely used and, consequently, is not a large consumer of energy.

Zinc Extraction

Roasting, sintering, and calcining are preliminary steps to extraction: pyroreduction, or leaching, and electrolysis. In pyroreduction, or pyrometallurgical reduction, three systems are in use: the Belgian, or horizontal, retort; the vertical retort; and the electrothermic furnace. All three processes are based on the action of carbon monoxide and solid carbon in sealed retorts at temperatures of 2200°F. On the other hand, the leaching and electrolytic process is considered to be a hydrometallurgical process.

Belgian Retort

The Belgian, or horizontal, retort is the oldest zinc smelting method. The basic retort is a batch system, and its charge is fired indirectly. The major aim of this and the other pyrometallurgical processes is closely controlled distillation — condensing and collection of liquid zinc with a minimum amount of oxidation or loss, or both. The basic retort is approximately 10 inches in diameter and 5-6 feet long. Each production unit within a horizontal-retort plant turns out only 100 pounds of zinc every 48 hours. Thus, to produce large amounts of zinc, a horizontal retort smelter must have many production units. For example, 10,000 retorts, with 5,000 charged per day, would be required to produce 90,000 tons/yr of zinc.

Horizontal retorting does not lend itself to effective automation; consequently, its efficiency suffers. Typically, a horizontal retort operates at fuel efficiencies of 5% or less because most of the fuel energy is lost up the flues. In addition, its zinc recovery is less than 90%.¹¹ Energy consumption for this process is about 60.0 million Btu/ton of zinc produced. The primary fuel used is natural gas.² Because

of its inefficiencies of operation, excessive operating costs, low productivity, and difficulty of controlling particulate emissions, this process is not likely to be used in the future.

Vertical Retorts

The vertical retort process for zinc recovery was developed in an effort to overcome the major problems of the horizontal process. Like the horizontal process, the vertical retort uses indirect heating to reduce the zinc calcines. Unlike the horizontal process, the vertical retort is continuous and can be mechanized. To be continuous, the retort is vertical so that the charge can pass through it by gravity. The charge must be briquetted to give free movement through the retort, to permit heat transfer to the center of the retort, and to provide sufficient porosity for the escape of gases. Because of these improvements, energy efficiency is about 10%; the typical energy consumption of a vertical retort is 18.0 million Btu/ton of zinc produced.² What makes this process possible is the use of briquettes as a charge; however, briquette production requires a major effort and reportedly consumes large amounts of energy. One company that uses vertical retorts reports that 36 million Btu of coal and coke per ton of distilled zinc is required for the briquetting process. However, this company claims an energy consumption by the retorts of only 10 million Btu/ton of distilled zinc for a total energy consumption of 46 million Btu/ton.¹⁰

Electrothermic Smelting

The electrothermic smelting process was developed in the U.S. and put into commercial operation in 1936. Unlike either the vertical or horizontal retorts, the electrothermic furnace is heated internally by electrical resistance. In the electrothermic furnace column, the charge of sinter, briquetted material, and coke is heated electrically to reaction zone temperatures of 1400⁰-2500⁰F. The charge is the current carrier. The most significant factor concerning electrothermic smelting is that it has an energy efficiency of 25-30%.¹¹ This process consumes about 10 million Btu/ton of zinc as electricity. An additional 21 million Btu/ton of zinc is consumed as coke, for a total of 31 million Btu/ton of zinc. However, if the energy for electric generation also is considered (assuming 33% efficiency), total energy consumption increases to 51 million Btu/ton.

Electrolytic Process

Electrolytic recovery is the fourth process used in the U.S. for producing zinc. In this process, the zinc sulfide concentrate that has been preroasted to produce calcine is transferred to a leaching operation, in which the calcine and dilute sulfuric acid are introduced into a series of tanks. Zinc oxide dust is added to precipitate the impurities. The resulting solution is filtered and subjected to electrolysis, in which the metallic zinc is deposited at the aluminum cathodes. The zinc cathodes then are melted in electric or reverberatory furnaces and subsequently cast into slabs. The basic electrolytic process is reasonably efficient, with an estimated energy efficiency of 25%.¹¹ The energy consumption per ton of zinc produced is estimated at 18.0 million Btu of natural gas for melting and 33.8 million Btu for electricity including electric generation, for a total of 51.8 million Btu.¹⁰

Refining

The zinc produced in the retorting process is transferred in molten form to fuel-fired reverberatory furnaces for refining. During refining, impurities, such as lead, iron, and cadmium, are removed. Typical energy requirements for this process are approximately 3 million Btu/ton of zinc produced. Upon completion of the refining process, the zinc is formed into slabs.

Energy Utilization Pattern

Depending upon the combination of processes used, the energy required to produce 1 ton of zinc slab varies from about 35 to 65 million Btu. In 1972, an estimated 38.0 trillion Btu of energy was consumed in the manufacture of primary zinc slabs, or an average of 55.2 million Btu/ton of zinc slab. In 1967, the industry consumed an average of 60.3 million Btu/ton of zinc produced.¹³ These data show an 8% improvement in energy utilization efficiency by this industry over a 5-year period. The main reason for this improvement is the closing of two horizontal retort plants, the most inefficient of the four processes used. These two plants had an annual production capacity totaling 113,000 tons.¹¹

Of the four zinc-smelting processes in use, the industry seems to be moving in the direction of the electrolytic process. Both the retort processes have shown significant decreases in total annual output in recent years, while the electrothermic process has just been holding its own. Although the vertical retort process and the electrothermic process will survive for a while, the electrolytic process is expected to ultimately prevail.¹¹ Of all the processes available, the electrolytic process is better able to conform to automation, customer quality demands, and air pollution regulations. As a result, the energy consumption rate per ton of zinc will remain virtually unchanged in the future as the process energy requirements, including energy consumed for electric generation, are about the same as the average energy consumption rate of all the processes currently in use.

New Technologies in Zinc Manufacturing

Because of the present state of affairs in the zinc industry, research and development of new technologies in the U.S. is at a virtual standstill. However, a new process for zinc manufacturing that is being used in other countries produces more than 10% of the total zinc production in the free world. This process, the Imperial Smelting Process (I.S.P.),⁴⁶ is strongly supported by the smelters that use it, but has not been put into operation in the U.S. In addition to producing zinc, the I.S.P. also produces lead bullion.

Basically, the I.S.P. furnace is similar to a standard lead blast furnace except that, in this case, the tuyeres project inside the line of the water jackets for better heat economy and the air blast is preheated in alloy-tube preheaters, which are fired by furnace gas. The charge to the furnace consists of sinter and hot coke, added alternately. The coke is preheated to 1500°F in a shaft-type furnace, also fired by furnace gas. The gases leaving the furnace are passed through condensers, where they are rapidly chilled to below 1100°F. The zinc vapors condense and go into solution in the molten lead. This solution is removed from the condensers and then cooled even further, causing the zinc and lead to separate into two layers according to their respective solubilities. These layers are separated easily.

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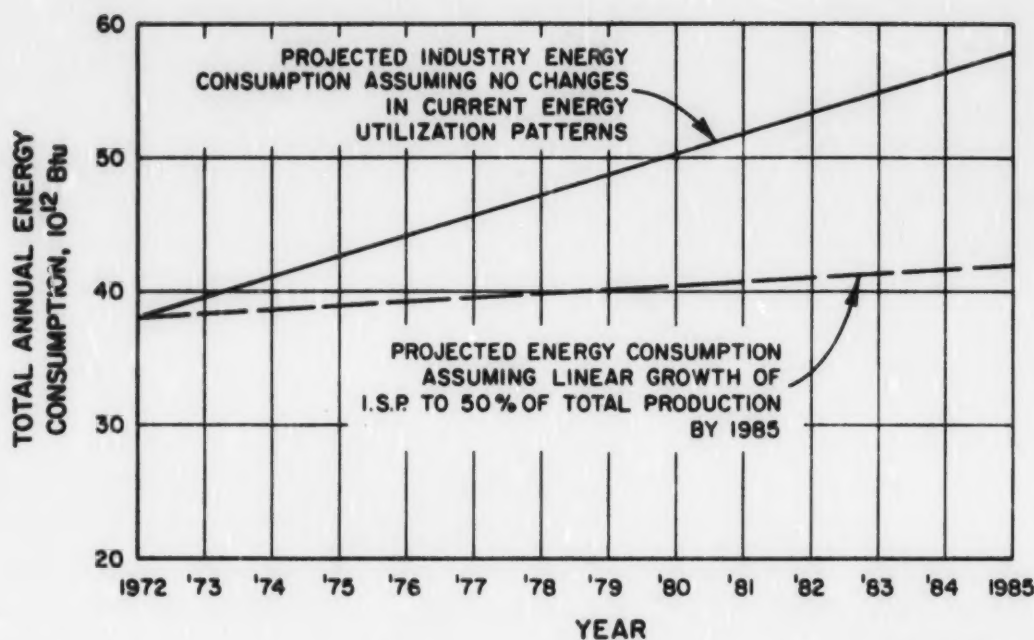
The energy requirements for this process are relatively low compared with those for other processes. Coke consumption is approximately 22.6 million Btu/ton of zinc produced. An additional 1.0 million Btu of electricity per ton and about 1.4 million Btu of furnace gas per ton are consumed. Thus, the total energy consumed by this process is about 25 million Btu/ton of zinc produced.

The current state of the I.S.P. is not ideal, but research to improve this process is continuing. These improvements include increasing furnace size, developing computer control, implementing oxygen enrichment, and using vacuum dezincing. All these improvements will make the process more economical by reducing costs and improving efficiencies. However, no data are available on the quantitative effects of these improvements.

Effect of New Technology on Energy Consumption

It is not clear at present just what effect the I.S.P. will have on the amounts of energy consumed by the zinc industry in the U.S. Currently, it is not used in this country; moreover, there is great opposition to it. Supporters of the process believe that it is a revolutionary process that will eventually smelt most of the world's zinc. Critics think that 1) the process is not flexible, requiring a carefully balanced lead-zinc feed; 2) it consumes great quantities of expensive metallurgical coke; and 3) it requires work-force procedures, namely, regular furnace shutdowns, for cleaning, requiring utilization of maintenance and operating crews on an irregular basis, which the unions in the U.S. would oppose.

In spite of these objections, the potential for reducing energy consumption by this industry is there, assuming acceptance of the process by U.S. manufacturers. Figure 3 shows the potential effect of this process on energy consumption, assuming that 50% of the zinc produced in the U.S. is produced by this process by 1985. These data also assume a 3.5% annual growth rate by this industry.



A-44-570

Figure 3. EFFECT OF IMPERIAL SMELTING PROCESS ON ENERGY CONSUMPTION BY DOMESTIC ZINC SMELTERS

Air Pollutant Emissions From Zinc Smelters

The primary air pollution emissions from zinc smelters are particulates and SO_x ; the latter are emitted primarily from plants that emit dilute off-gases from roasters and sinter machines. In 1972, an estimated 342,000 tons of sulfur dioxide was emitted by zinc smelters in the U.S., based on an emission rate of about 993 lb/ton of zinc produced.⁷ As in the other nonferrous metals industries, the primary method of control is recovery of the SO_x and conversion to sulfuric acid. Of the 15 zinc smelters currently in operation in this country, nine recover the SO_x from the off-gases, two smelt material very low in sulfur content, and four have no recovery units at all.³ At present, SO_x is recovered only from the roaster off-gases, because 93-97% of the sulfur in the feed to a zinc smelter is eliminated in roasting. Off-gases from the newer fluidized roasters contain from 7 to 12% sulfur dioxide, making them ideal, economically, for recovery and conversion to acid. The sulfur

dioxide concentrations in the off-gases from this and other types of roasters are shown in Table 3.

Table 3. CONCENTRATION OF SULFUR DIOXIDE IN OFF-GASES FROM ROASTERS IN ZINC SMELTERS

<u>Roaster Type</u>	<u>SO₂ Concentration, %</u>
Ropp Roaster	0.7-1.0
Multiple Hearth	4.5-6.5
Suspension	10-13
Fluid Bed	7-12
Fluid Column	11-12

With the exception of the Ropp roaster, the other roasters generate off-gases with high enough sulfur dioxide concentrations to make recovery and conversion to acid economical, although multiple-hearth roasters are marginal. Sintering machines, where used, are also sources of SO_x emissions, but the emission rate, which depends upon the sulfur content of the feed, is very low. The best way to reduce sulfur dioxide emissions from this process is to use feed with the lowest possible sulfur content. Because the concentration of sulfur dioxide in the off-gases from sintering machines is so low, no attempts are made to recover it. (See Table 4.)

Table 4. SULFUR OXIDE GENERATION AND RECOVERY AT U.S. ZINC SMELTERS IN 1969⁹

<u>Process</u>	<u>Sulfur Equivalent</u>		<u>% Recovered</u>
	<u>Generated</u>	<u>Recovered</u>	
	tons/yr		
Roasters	697,300	461,600	66.2
Sinter-Roast Machines	60,100	0	0
Sintering Machines	22,700	0	0
Cokers and Retorts	2,600	0	0
Total	782,700	461,600	59.0

The SO_x emissions from the zinc extraction processes are very low and thus offer no real possibilities for recovery.

The other major air pollutant emission is particulate matter. Of all the processes used in zinc smelting, the fluid-bed roasters and the retorts are responsible for the largest percentage of the total particulate matter emitted. The data presented in Table 5 indicate that particulate emissions from these two sources alone accounted for 60% of the total emissions in 1972 in spite of the controls used.

Table 5. PARTICULATE EMISSIONS FROM ZINC SMELTERS IN 1972

<u>Process</u>	<u>Emission Factor⁵</u>	<u>Control Efficiency</u>	<u>Emissions, tons/year</u>
Ore Crushing	2 lb/ton ore	0.0	12,400
Roasting			
Fluid Bed, Suspension	2000 lb/ton zinc	0.98	10,300
Ropp, Multiple Hearth	333 lb/ton zinc	0.85	2,580
Sintering	180 lb/ton zinc	0.95	1,860
Retorts	49 lb/ton zinc	0.0	16,860
Materials Handling	71 lb/ton zinc	0.32	<u>1,640</u>
Total			45,640

The other major source was the ore-crushing process. Particulate emissions can be controlled by normal methods, such as electrostatic precipitators and baghouse filters, regardless of the source. Some difficulty is encountered in collecting the sinter fumes electrically because of their inherently high electrical resistivity. However, with proper control of gas temperatures and moisture content, efficient collection can be maintained. As things currently stand within this industry, the electrolytic process will assume the major part of the zinc production load in the future. Particulate emissions from this process are only 5 lb/ton of zinc without controls. On this basis, if 100% of the zinc had been manufactured by this process in 1972, a total of 1032 tons of particulates would have been emitted, resulting in a total reduction from all zinc smelters of 35%. Apparently, such a conversion to this process by the industry would have a significant impact on the particulate emission problem.

Effect of New Technology on Air Pollutant Emissions

The emergence of the I.S.P. in the U.S., should it occur, is not likely to have a significant effect on air pollutant emissions because the primary sources of emissions, namely, the roasters and sintering machines, are still required in this process. In addition, there is no other new technology that will affect pollutant levels in the near future.

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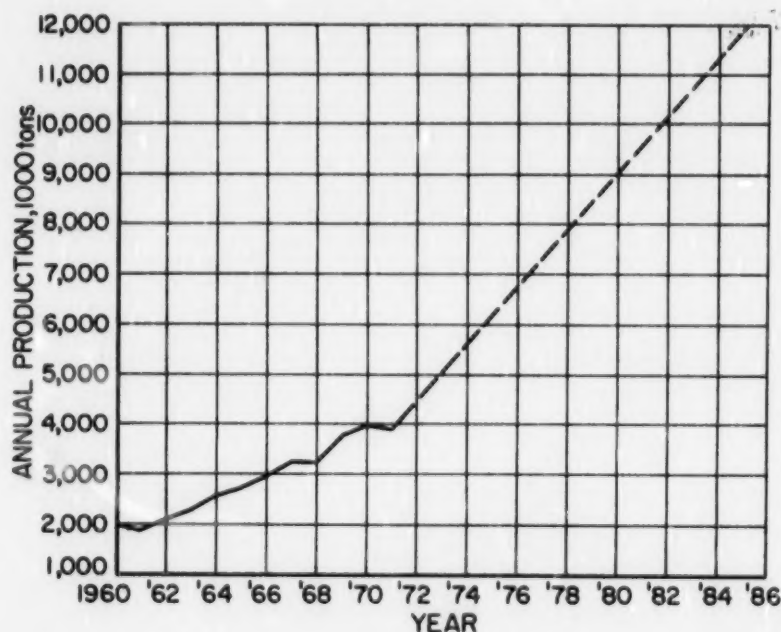
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XIII. SIC CODE 3334 - PRIMARY ALUMINUM

SIC Code 3334 pertains to those establishments primarily engaged in producing aluminum from alumina and in refining aluminum by any process. Establishments engaged in rolling, drawing, or extruding aluminum are classified elsewhere.

The primary aluminum industry is growing at a greater rate than any of the other nonferrous metal industries. Historically, production of aluminum in the U.S. doubles every 10 years (Figure 1), and this growth rate is expected to continue.

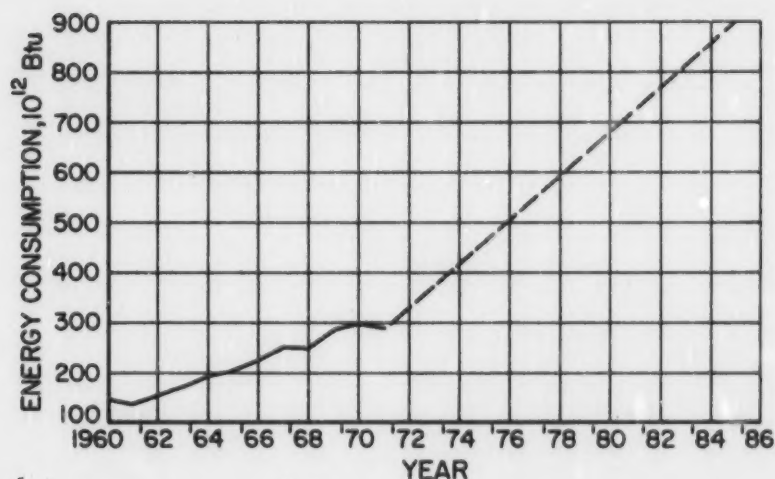


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Figure 1. ANNUAL PRODUCTION OF PRIMARY ALUMINUM WITH PROJECTION TO 1985

Between 1960 and 1970, the annual production of primary aluminum increased from 2 million to almost 4 million tons.¹ By 1985, production is expected to increase to 12 million tons/yr,⁴ an increase of 200% over current production rates, in spite of the depressed growth rate in the early 1970's due to an oversupply situation.

Energy consumption by the primary aluminum industry was about 295 trillion Btu in 1971.⁷ This figure does not include the fuel consumed by the electricity-generating stations, nor does it include fuel consumed for use as carbon anodes in the electrolysis process. By 1985, the total annual energy consumption of this industry will be about 900 trillion Btu, assuming no changes in energy utilization efficiency (Figure 2).



A-54-721

Figure 2. ANNUAL ENERGY CONSUMPTION FOR POWER AND HEAT BY THE ALUMINUM INDUSTRY WITH PROJECTIONS TO 1985

This is more than 3 times the current rate of consumption. However, there are significant inefficiencies in the energy consumption of this industry, and several new processes that are available will probably reduce the energy consumed by this industry. The most important new process, which was just developed, according to its developers, consumes 30% less energy than the process currently used. Details on this process are not available, but, in time, it is expected to revolutionize the industry.

Air pollutant emissions from primary aluminum plants are composed primarily of particulates and fluorides, the most serious emissions occurring from the potlines. However, control methods that exist remove up to 98% of these emissions from the effluent gas streams, although there is no inventory of methods in use to indicate the real emission rates for this industry.

Primary Aluminum-Manufacturing Processes

In general, aluminum production is divided into three operations: mining the bauxite, refining the bauxite into alumina, and smelting the alumina into aluminum. (See Figure 3.)

Mining

Bauxite is the ore from which aluminum is produced. Because most bauxite lies at or near the surface, it usually is mined by open-pit methods. After the ore is dug up, it is transferred by truck and rail to a point of processing. There the bauxite is ground down to uniformly sized particles and passed into a rotary kiln in which excess moisture is removed.

The drying process is a relatively low-temperature process; it requires temperatures of only 1100°F. Consequently, heat losses are minimized and energy utilization efficiency is relatively high, about 40%. The energy consumed in drying is 1.0 million Btu/ton of ore dried. Drying accounts for only a small percentage of the energy consumed domestically by the aluminum industry because only 15% of the bauxite consumed in the U.S. is obtained from domestic sources. Thus, in 1971, only 2.3 trillion Btu, less than 1% of the industry's total annual energy consumption, was used for drying.

Refining

The refining of bauxite to obtain alumina is achieved by the Bayer Process. The objective of this process is to separate out the impurities, which include iron oxide, silica, and titanium dioxide.

The first step in the Bayer Process is digestion of the bauxite into a solution of hot caustic soda. The dried bauxite is mixed in slurry tanks with a strong caustic soda solution. The mixture is pumped into large digesters in which it is heated with steam under pressure. The

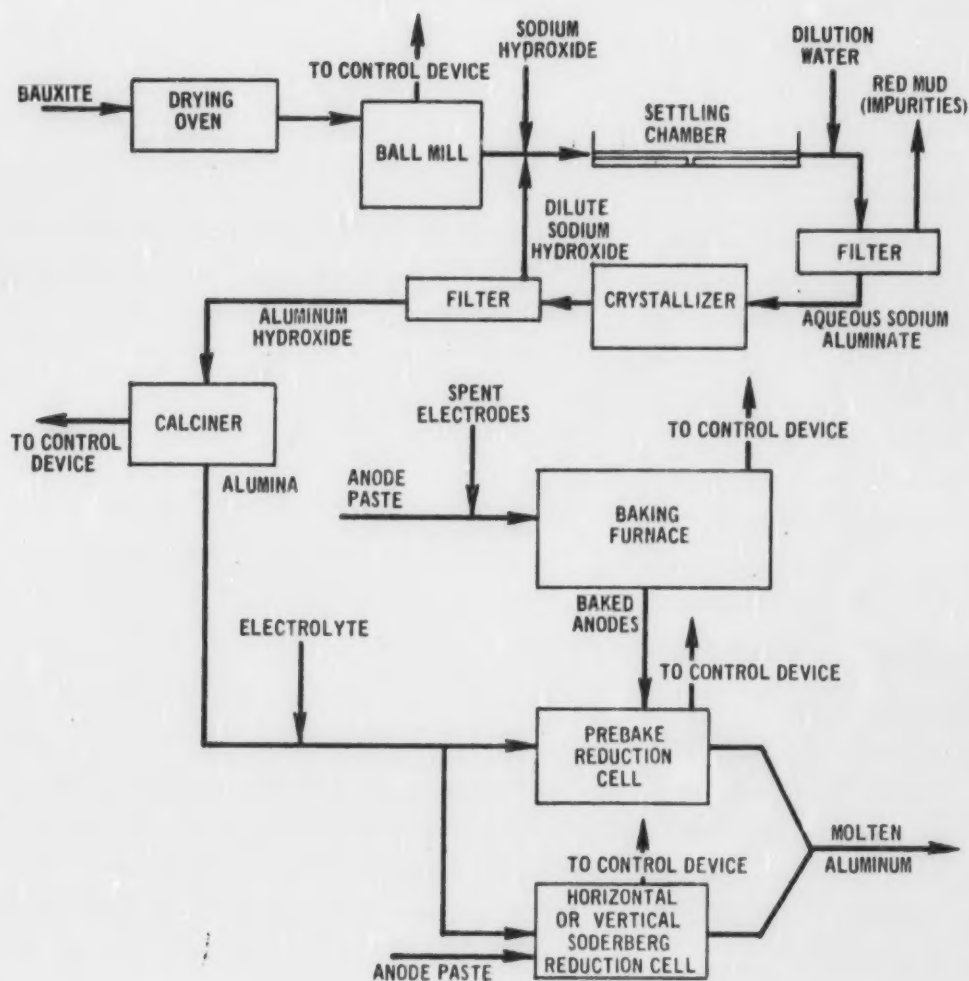


Figure 3. SCHEMATIC DIAGRAM OF PRIMARY ALUMINUM PRODUCTION PROCESS^B

alumina in the bauxite is dissolved in the caustic soda, forming a sodium aluminate solution. The impurities, which are insoluble, remain as solids. The mixture is passed through a series of pressure-reducing tanks and filter presses. Cloth filters hold back the solids - known as "red mud" - but allow the liquid, which contains the dissolved alumina, to pass.

At many plants, the red mud is discarded, but at some — where lower grade ores are refined — this mud is sintered with limestone and soda ash to recover a sodium aluminate solution. This solution then is returned to the digesters for processing through the remaining steps of the refining process.

After the solution containing the alumina passes through the filters, it goes into a cooling tower and then into precipitators, which are steel structures resembling farm silos. As the solution cools, it is seeded with sizable amounts of crystalline alumina hydrate to hasten crystal separation. Eventually, a precipitate of hydrated alumina settles out of solution. This precipitate is filtered from the solution, washed, and then heated in kilns at 1800°F. The crystals are dried, and the water is driven off, leaving commercially pure alumina. The dried alumina is shipped to an aluminum smelter for reduction.

The Bayer Process consumes from 10 to 15 million Btu of thermal energy per ton of alumina produced. Natural gas is the preferred fuel; consequently, most Bayer Process plants are located in areas of lower cost natural gas. To produce 1 ton of aluminum in the reduction process, approximately 2 tons of alumina is required. Thus, the 7.8 million tons of alumina produced in 1971 consumed approximately 115 trillion Btu of natural gas.

Smelting

Smelting is the process that breaks alumina down into its two components, aluminum and oxygen. The basic smelting process is the Hall Process, which has been used by the industry since 1886. In this process, alumina is dissolved in a bath of molten cryolite — sodium aluminum fluoride — in large electric furnaces. These pots, as the furnaces are called, are deep rectangular steel shells lined with carbon and connected electrically in series to form a "potline."

High-amperage, low-voltage direct current is passed through the cryolite bath — by means of carbon anodes suspended in each pot — to the bottom of the pot, which serves as the cathode. The molten aluminum formed as a result of this electrolysis goes to the bottom of the pot, and the oxygen combines with the carbon anode to release carbon

dioxide. The layer of molten aluminum that covers the carbon lining at the bottom of the pot becomes the cathode. Additional alumina is added to the bath to replace that consumed in the reduction process. Heat generated by the electrolysis maintains the cryolite bath in a molten state, so that the additional alumina charges are dissolved. Periodically, molten aluminum is siphoned and cast into ingots or alloyed. The resulting aluminum is at least 99.5% pure.

The primary source of energy for this process is electricity, which is consumed at the rate of 55-60 million Btu/ton of aluminum produced. This does not include the fuel consumed for electricity generation.

The three types of pots used in this process are distinguished by the type of anode configuration: prebaked, horizontal-stud Soderberg, and vertical-stud Soderberg. The major portion of aluminum produced in the U.S. (61.9% of 1970 production) is processed in prebaked cells. In this type of pot, the anode consists of blocks that are formed from a carbon paste and baked in an oven prior to use in the cell. These blocks are attached to metal rods and serve as replaceable anodes. As the reduction proceeds, the carbon is gradually consumed. The rate of consumption is 0.45-0.55 pound of electrode per pound of aluminum produced, which is typical of all three types of pots.

The second most commonly used pot (25.5% of 1970 production) is the horizontal-stud Soderberg. This type of cell uses a continuous carbon anode in which a mixture of pitch and carbon aggregate is periodically added at the top of the superstructure, and the entire assembly is moved downward as the carbon burns away. The cell anode is contained by aluminum sheeting and perforated steel channels, through which electrode connections, called studs, are inserted in the anode paste (the pitch and carbon aggregate mixture). As the baking anode is lowered, the lower row of studs and the bottom channel are removed, and the flexible electrical connectors are moved to a higher row.

The vertical-stud Soderberg is similar to the horizontal-stud pot, except that the studs are mounted vertically in the cell. The studs must be raised and replaced periodically, which is a relatively simple operation.

Energy Utilization Pattern

Approximately 75 million Btu of energy is consumed in an aluminum plant for power and heat in the production of 1 ton of aluminum. However, fossil fuels also are consumed in the manufacture of the carbon electrodes used in the electrolytic process. And finally, because electricity is the primary form of energy consumed, fossil-fuel consumption for electricity generation also should be considered.

The electrolytic process for converting alumina to aluminum consumes about 0.6 ton of carbon electrodes per ton of aluminum produced. Because 40,000 Btu of fossil fuel (including petroleum, coke, and pitch) is required to produce 1 pound of carbon, the fuel value of the carbon amounts to about 48 million Btu/ton of aluminum produced.

According to the 1972 Census of Manufactures report⁷ on fuels and electricity consumed, almost 52% of the energy consumed directly by the aluminum producers was electricity, a total of slightly more than 150 trillion Btu. Because of the low efficiency of electricity generation, however, the total fuel value for electricity consumed is about 3 times higher. Assuming a 33% efficiency for electricity generation and transmission, the actual fuel value of the electricity consumed is 455 trillion Btu, or almost 120 million Btu/ton of aluminum produced. Note that almost one-half of the electricity consumed by aluminum producers is generated hydroelectrically.⁶ Consequently, aluminum plants tend to be located near the sources of this low-cost electricity, primarily in the TVA area, the Ohio Valley, and the Pacific Northwest. Furthermore, fossil fuels consumed for electricity generation account for only one-half of the electricity consumed by the industry. As a result, only 230 trillion Btu of fossil fuel was consumed for the generation of electricity by aluminum producers in 1971. Of the electricity consumed by aluminum producers in 1971, 75 trillion Btu was generated hydroelectrically. The actual total fuel value of the electricity consumed by aluminum producers was 305 trillion Btu, or 78 million Btu/ton of aluminum produced. Given these considerations, the total amount of fuel consumed by aluminum producers in 1971, including electricity generation and the production of carbon anodes, was 635 trillion Btu, or 163 million Btu/ton of aluminum produced.

For the energy consumed by the aluminum industry, Figure 4 compares the case in which energy consumed for electricity generation is included with the case in which it is excluded. However, there has been a trend in recent years toward hydroelectric power. From 1960 to 1969, the percentage of electricity from hydroelectric sources consumed by aluminum producers increased from 39.1 to 48.3%. If this trend continues, the total fuel value of energy consumed by the aluminum industry will be lower than that projected by the top curve in Figure 4 as a result of a decrease in fossil fuels consumed for electricity generation.

New Technologies in the Manufacture of Aluminum

The Hall-Heroult Process for converting alumina to aluminum is the greatest energy-consuming process in the manufacture of aluminum. As a result, much work has been done to develop means for lowering its energy consumption. The most significant development to date is a new process that reportedly consumes 30% less electrical energy than the traditional Hall-Heroult Process, which has been in use since 1886. However, details of this process, developed by Alcoa, are not available at present.

If energy consumption is going to be reduced, the efficiency of the electrolytic process will have to be increased. Currently there is great interest in the concept of increasing the efficiency by adding lithium salts to the cryolite baths. Lithium salts are particularly attractive because of their effectiveness in lowering the freezing point and increasing the electrical conductivity of the electrolyte. Several tests with lithium fluoride on aluminum potlines have resulted in a 10-12% increase in production and a 2-3% savings in power consumption.² In addition, the net carbon consumption was about 5% lower than in a normal cell. Thus, additional energy is saved by the reduced carbon consumption.

During the past 30 years, much research has been done to develop methods for processing clay into alumina suitable for aluminum production.³ This research resulted in the development of several processes for treating the clay; in addition, many variations of each process have been developed. In general, these processes utilize chemical means for reaching the desired product, and in some cases, high-temperature heating (2000°F) in fuel-fired furnaces and kilns is required. Although

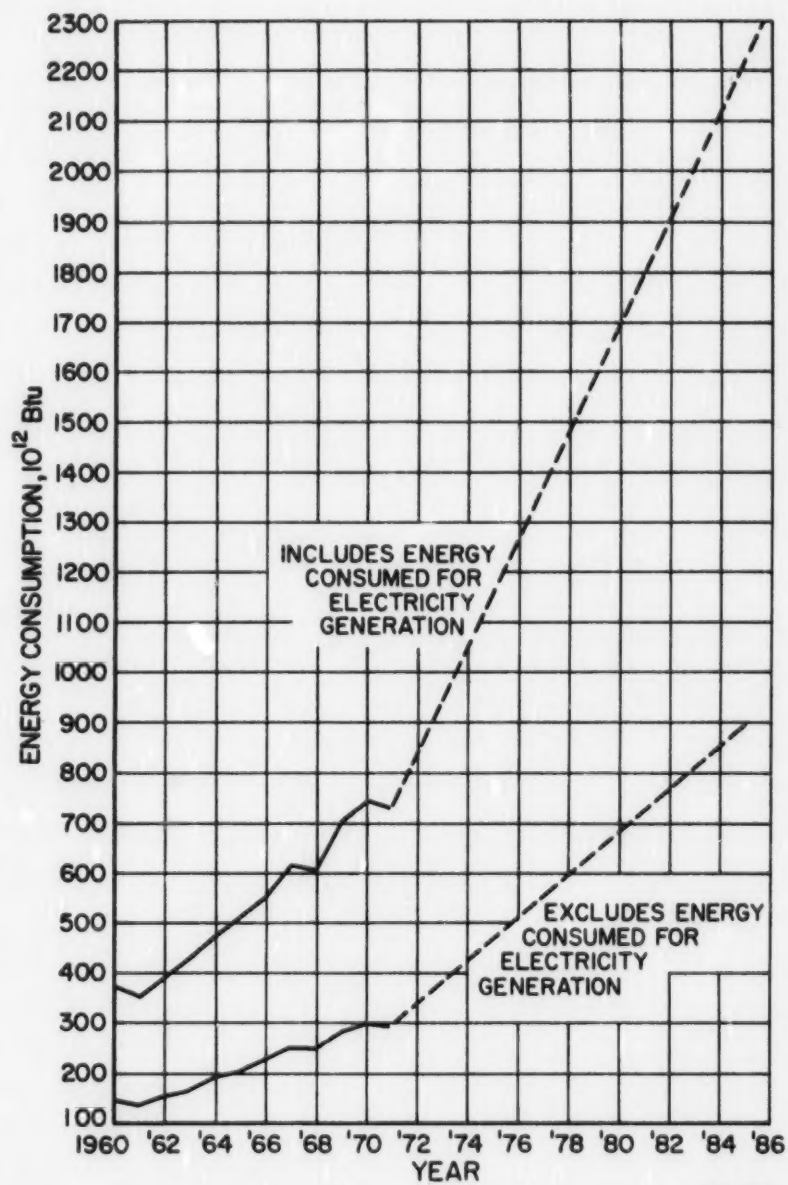


Figure 4. ANNUAL ENERGY CONSUMPTION BY ALUMINUM INDUSTRY WITH AND WITHOUT ELECTRICITY GENERATION

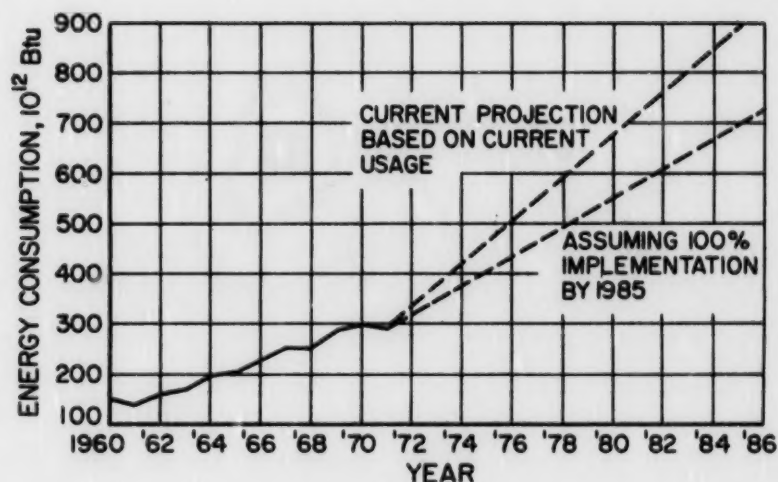
there are many proposed processes, they can be categorized into three major classifications: acid-leaching, alum intermediate, and alkaline sinter. Energy consumption by these processes is variable, and no operating data are available to allow even an estimate of the range to be made. At present, none of these processes has been commercialized nor are they likely to be, until costs are lower, or until the prices for the conventional route rise sufficiently. Such a rise would be due primarily to increases in fuel costs or increases in the cost of bauxite. At present, only fuel costs seem to be rising rapidly. Increases in bauxite costs have been held to a minimum because of the current oversupply situation. Currently, the Bayer Process is 20% less costly than the least costly of these new processes. As a result, the research objective is to lower costs by improving existing processes or developing improved versions of these processes. Eventually, the process with the lowest cost probably will be commercialized.

Effect of New Technologies on Energy Consumption

At the present rate of consumption, the total amount of energy consumed by the aluminum industry annually is expected to increase threefold by 1985. However, the potential for reducing energy consumption is good, especially in light of the recent announcement of Alcoa's new process. It is difficult to assess the impact of this process on the industry without details on the time required for implementation. Figure 5 shows that if full implementation were achieved by 1985, the projected energy consumption would be reduced by nearly 25%.

On the other hand, the addition of lithium salts to the cryolite bath, as previously described, reduces total energy consumption by about 5%. Implementation of this technology apparently does not require extensive changes in operation, large increases in capital costs, or other such prohibitive actions on the part of the aluminum producer. Consequently, short-range implementation to achieve the reduction in energy consumption seems feasible.

As previously stated, there are no commercialized processes for converting clay to alumina; consequently, no operating data are available. Furthermore, estimates of expected energy consumption also are not available. As a result, the effects of these processes on the total energy consumption of the industry is indeterminable at present.



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Figure 5. EFFECT OF IMPLEMENTATION OF NEW ALCOA PROCESS ON ENERGY CONSUMPTION OF ALUMINUM INDUSTRY (Excluding Energy Consumed for Electricity Generation)

Air Pollutant Emissions From Aluminum-Manufacturing Processes

Air pollutants originate from several processes in an aluminum-manufacturing plant, but the most objectionable and most difficult to control are those from the potlines. Aside from carbon monoxide and carbon dioxide, which are released as a result of the reaction of oxygen from the alumina with the carbon anode, emissions from the potlines include sulfur dioxide, derived from the sulfur in the petroleum coke and tar used to make the carbon anodes; particulates of vaporized bath materials; hydrogen fluoride gas, the result of hydrolysis of some fluoride salt vaporization; alumina, cryolite, and aluminum fluoride dusts; and minor quantities of a number of other pollutants.⁵ Other sources of emissions include the bauxite-grinding operation, the calcination operation, materials handling, and anode preparation.

From the point of view of potential damage to the areas surrounding an aluminum plant, the most important effluents are gaseous and particulate fluorides released from the molten bath electrolyte of the potlines. In general, total fluoride concentrations in the waste gases from the various types of cells are approximately equal. However, the relative amounts of gaseous and particulate fluorides emitted depend upon the mechanisms for removing and treating the gases. Table 1 summarizes the emission rates of total particulates and gaseous and particulate fluorides from the various types of smelters. Application of the best demonstrated pollution abatement equipment to collect the primary potline effluents would result in estimated total fluoride emissions of 1.2-4.7 lb/1000 lb of aluminum produced, depending upon the type of potline, compared with 18.5-23 lb/1000 lb of aluminum produced⁵ without such equipment. The addition of scrubbing equipment on the secondary streams would reduce the total fluoride emissions even further to 0.8-2.0 lb/1000 lb of aluminum. Application of this technology by the entire industry would raise the overall control efficiency of the industry from the present 74 to 92%. However, invested industry expenditures for pollution control would increase more than threefold.⁵

Table 2 summarizes the emissions from primary aluminum production processes other than the potlines. Also included in this table are the effects of various types of control equipment. Emission factors for other pollutants such as sulfur dioxide and hydrocarbons from prebake anode furnaces are not available.

Effect of New Technologies on Air Pollutant Emissions

The effects, if any, of the new Alcoa process on air pollutant emission rates from potlines are not known at present. However, the other new processes discussed above are not expected to affect air pollutant emissions from potlines. On the other hand, the processes for converting clay to alumina are of interest in the more distant future (beyond 1985) because no waste products are given off. (The various products - aluminum hydroxide, cement, and combustion gases - are all utilized.) Even so, the only emissions affected by the advent of such a process would be particulates emitted during the grinding of the bauxite in the currently used process. Based on an estimated production of 12 million tons of aluminum in 1985 and assuming 100% implementation of

Table 1. ALUMINUM SMELTER EFFLUENTS⁵

Component	New Prebake ^e			Old Prebake ^e			VS Soderberg			HS Soderberg		
	Total	Prim.	Sec.	Total	Prim.	Sec.	Total	Prim.	Sec.	Total	Prim.	Sec.
Solid Fluorides ^a	10	9.5	0.5	10	8.0	2.0	3	1.5	1.5	10	8.0	2.0
Quantity, lb/Mlb Al	—	61	0.32	—	51	1.3	—	47	0.7	—	37	0.9
Loading, mg/m ³	13	12.6	0.4	13	11.7	1.3	20	17.0	3.0	13	11.7	1.3
HF	—	81	0.25	—	75	0.8	—	543	1.4	—	53	0.6
Quantity, lb/Mlb Al	23	22.1	0.9	23	19.7	3.3	23	18.5	4.5	23	19.7	3.3
Loading, mg/m ³	—	142	0.57	—	126	2.1	—	590	2.1	—	90	1.5
Total Fluoride ^b	20	19.0	1.0	20	16.0	4.0	3	1.5	1.5	20	16.0	4.0
Quantity, lb/Mlb Al	—	122	0.64	—	103	2.6	—	47	0.7	—	73	1.8
Loading, mg/m ³	48	46.1	1.9	48	41.3	6.7	39	25.9	13.1	49	38.2	10.8
Total Solids	—	295	1.2	—	265	4.4	—	826	6.1	—	174	18.4
Quantity, lb/Mlb Al	15-50	14-48	1-2	15-50	14-45	1-5	15-50	13-43	2-7	15-50	14-45	1-5
Loading, mg/m ³	—	90-300	0.6-1.2	—	90-300	0.6-3.2	—	420-1380	0.9-3.2	—	64-206	0.4-2.3
Diluent Air ^d	27.5	2.5	25	27.5	2.5	25	35.5	0.5	35	18.5	3.5	35
Quantity, lb/Mlb Al	—	95	—	—	80	—	—	50	—	—	80	—
Loading, mg/m ³	—	97	—	—	90	—	—	85	—	—	90	—
Collection Efficiency	—	96.0	—	—	95.6	—	—	80.4	—	—	85.6	—
10 ⁴ cu ft/Mlb Al	—	—	—	—	—	—	—	—	—	—	—	—
Solid F, %	—	—	—	—	—	—	—	—	—	—	—	—
HF, %	—	—	—	—	—	—	—	—	—	—	—	—
Total F, %	—	—	—	—	—	—	—	—	—	—	—	—

^a Includes fugitive dusts from cell room.^b Reported range 12.8 to 33.0 lb/1000 lb Al.^c 10 lb SO₂/1000 lb Al/percent Si in anode coke.^d Represents total cell room air.^e It is easier to control effluents from new prebakes than from old prebakes.

Table 2. AIR POLLUTANT EMISSIONS FROM PRIMARY
ALUMINUM PRODUCTION PROCESSES EXCLUDING POTLINES^a

Type of Operation	Total Particulates ^b	Gaseous Fluorides (HF)		Particulate Fluorides (F)
		lb/ton		
Bauxite Grinding ^a				
Uncontrolled	6.0	Negl	NA ^e	
Spray Tower	1.8 ^c	Negl	NA	
Floating-Bed Scrubber	1.7	Negl	NA	
Quench Tower and Spray Screen	1.0	Negl	NA	
Electrostatic Precipitator	0.12	Negl	NA	
Calcining of Aluminum Hydroxide ^a				
Uncontrolled	200.0	Negl	NA	
Spray Tower	60.0	Negl	NA	
Floating-Bed Scrubber	56.0	Negl	NA	
Quench Tower and Spray Screen	34.0	Negl	NA	
Electrostatic Precipitator	4.0	Negl	NA	
Anode Baking Furnace				
Uncontrolled	3.0 (1.0-5.0) ^d	0.93	Negl	
Spray Tower	NA	0.0372	Negl	
Dry Electrostatic Precipitator	1.13	0.93	Negl	
Self-Induced Spray	0.06	0.0372	Negl	

^a Emission factors for bauxite-grinding expressed as pounds per ton of bauxite processed. Factors for calcining of aluminum hydroxide expressed as pounds per ton of alumina produced. All other factors in terms of tons of molten aluminum produced.

^b Includes particulate fluorides.

^c Controlled emission factors are based on average uncontrolled factors and on average observed collection efficiencies.

^d Numbers in parentheses are ranges of uncontrolled values observed.

^e No information available.

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such a process, particulate emissions from aluminum smelters would be lower by about 400 tons/yr. This estimate is based on current emission levels of 0.12 lb/ton of bauxite processed with electrostatic precipitators. Beyond this process, emission reductions will come about primarily through improvements in control equipment.

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XIV. ELECTRICITY AND STEAM GENERATION

Approximately 43% of the fossil fuels consumed by industry for power and heat in 1971 was used in boilers.^{2, 7} In addition, more than 13% of the total amount of energy consumed by industry for power and heat in 1971 was electricity.⁷ Consequently, this last section of the report discusses electricity and steam generation.

Industrial Boilers

The use of fossil fuels to generate steam varies considerably from one industry to another. Approximately 10% of the fossil fuels consumed by industries in SIC Code 32 (stone, clay, and glass) is used to generate steam.² By comparison, about 95% of the fossil fuels consumed by industries in SIC Code 26 (paper and allied products) is used to generate steam.²

All the boilers used in industry are classified as intermediate size, that is, larger in capacity than residential boilers (200,000 Btu/hr) and smaller than that equivalent to 50 megawatts electrical (500,000 pounds of steam per hour).² The three basic types of boilers used are water-tube, fire-tube, and cast iron. The efficiency of fuel utilization of these boilers is usually 80% or higher. Consequently, reductions in total energy consumption by boilers can be achieved by reducing the steam load by 1) switching from steam to direct-fired processes when feasible and 2) properly maintaining all the steam plant facilities, including properly insulating all steam lines and repairing leaks when they occur. For example, a recent survey of the operations of a division of a large chemical company indicated that up to 8% of the existing steam traps were blowing steam.⁴ Worn steam jets with excessive steam pressure were found, accounting for millions of Btu's lost every hour, as well as innumerable steam-line leaks. Under these circumstances, much energy undoubtedly is being wasted daily by industry, energy that without too much difficulty could be saved.

Table 1 summarizes estimates of the percentage of fuel that is used in manufacturing to fire boilers. Note that other fuels also are burned under boilers, depending on the industry and the availability of such fuels. For example, in the paper industry bark is used as a boiler fuel and in the steel industry blast-furnace gas and coke-oven gas, when available, are used as boiler fuels. This report does not include these fuels because they are not considered primary fuels. The data in Table 1 and data on fuel consumption

by each industry indicate that the paper, food, and chemical industries are prime candidates for significant reductions in energy consumption. Estimated reductions of 10-20% of the fuel consumed under boilers could be achieved by these industries. Such reductions would represent substantial savings in the total energy consumption of industry. Such reductions also would result in substantial reductions in industry expenditures for fuel without increasing operating costs significantly.

In 1971, approximately 4900 trillion Btu of fossil-fuel energy was consumed by industry in boilers. ^{2,7} Of this amount, 1700 trillion Btu was consumed as coal, 2100 trillion as natural gas, and 1100 trillion as fuel oil. It is estimated that the consumption of fossil fuels under industrial

Table 1. PERCENTAGE OF FUEL IN
MANUFACTURING USED IN BOILERS²

Industry	Percent Burned under Boilers		
	Coal	Oil	Gas
Food	100	100	90
Tobacco	100	85	50
Textile	100	90	80
Apparel	100	90	80
Lumber	100	90	70
Furniture	100	90	50
Printing	100	90	85
Chemicals	75	40	30
Petroleum	90	40	30
Rubber, Plastics	100	65	40
Leather	100	85	50
Stone, Clay, Glass	10	10	10
Fabricated Metal	90	70	20
Machinery	90	70	20
Elec. Machinery	90	70	20
Transp. Equipment	90	80	20
Instruments	90	80	45
Primary Metals	90	10	10
Paper	100	95	93
Miscellaneous	70	50	50

boilers will nearly double by 1985.² The future distribution of fuels consumed under boilers is difficult to estimate, but coal and fuel oil consumption is likely to increase in proportion to natural gas consumption because of the reduced availability of natural gas.

Air Pollutant Emissions From Industrial Boilers

Air pollutant emissions from industrial boilers consist primarily of SO_x , NO_x , and particulates. In some cases, hydrocarbons and carbon monoxide also are emitted, but these are controllable by maintaining proper combustion. The emission rates of these pollutants vary considerably and depend on the type of fuel consumed. Table 2 shows emissions typical of industrial boilers fired by each type of fossil fuel.

Particulates

In 1971 an estimated 2.3 million tons of particulate matter was emitted by industrial boilers. This estimate is based on an average emission rate of 0.95 lb/million Btu of fuel consumed,² assuming that the relative ratios of fuel consumed under industrial boilers have remained unchanged since 1967. At the present rate, particulate emissions will nearly double by 1985. (See Figure 1.) However, any shifts in fuel utilization patterns will have a significant effect. If the projected shift toward coal and fuel oil occurs because of a shortage of natural gas, particulate emissions will increase. In general, industrial-size boilers, many of which are used for space heating and thus are only used seasonally, are not controlled. By imposing control measures on this equipment, immediate reductions in particulate emissions would result.

SO_x

In 1971, an estimated 4.2 million tons of SO_x was emitted by industrial boilers, assuming an estimated average emission rate of 1.7 lb/million Btu consumed.² As in the case of particulates, SO_x emissions are sensitive to the type of fuel consumed. Consequently, a future shift toward coal and fuel oil will result in an increase in SO_x emissions. Current attempts to alleviate this problem emphasize the use of low-sulfur fuels and waste-gas treatment, although the latter approach is generally too expensive to be practical for industry. Unfortunately, the availability of low-sulfur fuels also is diminishing rapidly. Consequently, SO_x emissions can be expected to increase in the future.

Table 2. EMISSION FACTORS FROM INDUSTRIAL BOILERS⁸

Pollutant	Fuel			
	Natural Gas, lb/10 ⁶ Btu ^f	Fuel Oil		Coal, d lb/10 ⁶ Btu ^f coal burned
		Residual, lb/10 ⁶ Btu ^f	Distillate, lb/10 ⁶ Btu ^f	
Particulates	0.018	0.15	0.10	0.50A-0.62A ^e
SO _x	0.0006	1.06S ^b	0.96S ^b	14.8S ^b
NO _x	0.120-0.230 ^a	0.27-0.53 ^c	0.27-0.53 ^c	0.58-0.69
Carbon Monoxide	0.017	0.027	0.027	0.04-0.08
Hydrocarbons	0.003	0.02	0.02	0.01-0.04
Aldehydes	--	0.007	0.013	0.0002

^a Use 120 for smaller industrial boilers (<500 boiler horsepower) and 230 for larger industrial boilers (>7500 boiler horsepower).

^b The letter S is weight percentage of sulfur in fuel, which should be multiplied by value given to obtain factor.

^c Use 40 for tangentially fired units and 80 for horizontally fired units.

^d First value is for boilers consuming 10 to 100 X 10⁶ Btu/hr; second value is for boilers consuming greater than 100 X 10⁶ Btu/hr.

^e The letter A is weight percentage of ash in coal, which should be multiplied by value given to obtain factor.

^f Pounds per 10⁶ Btu at 1000 Btu/CF, 150,000 Btu/gal, 13,000 Btu/lb.

NO_x

In 1971, an estimated 1.08 million tons of NO_x was emitted from industrial boilers based on the emission factors in Table 2. A number of factors are involved in the formation of NO_x in the combustion of fossil fuels, including flame temperature and the nitrogen content of the fuel. Consequently, the type of fuel as well as the boiler size affect the rate of NO_x emissions. More than 40% of the NO_x emissions from coal- and oil-fired boilers is due to the nitrogen content in the fuel. The nitrogen content of natural gas is much lower than that of coal or oil, and consequently, NO_x emissions from natural-gas-fired boilers due to fuel nitrogen are relatively low. As a result, shifts toward coal and oil will result in higher NO_x emissions. Several studies on ways to reduce NO_x emissions are being conducted. Some of the proposals include the use of flue-gas recirculation and water injection.

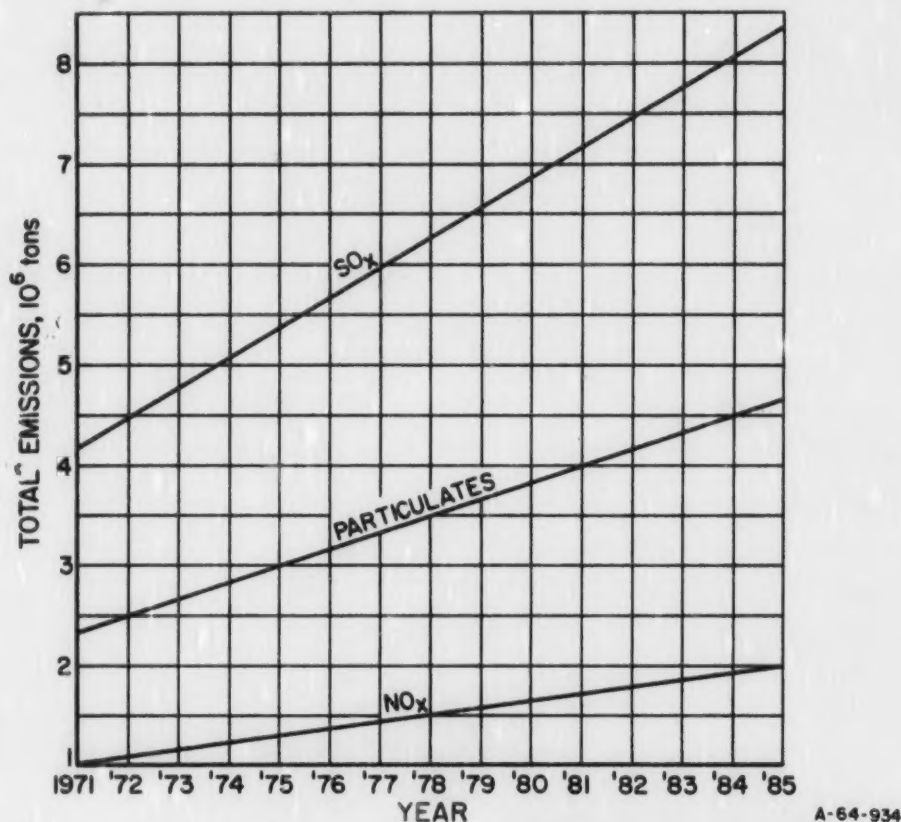


Figure 1. PROJECTED ANNUAL EMISSIONS OF SELECTED POLLUTANTS FROM INDUSTRIAL BOILERS

But because the mechanism of NO_x formation is not clearly understood, solutions to this problem appear to be in the distant future. Consequently, NO_x emissions can be expected to continue to increase in the foreseeable future.

Other Emissions

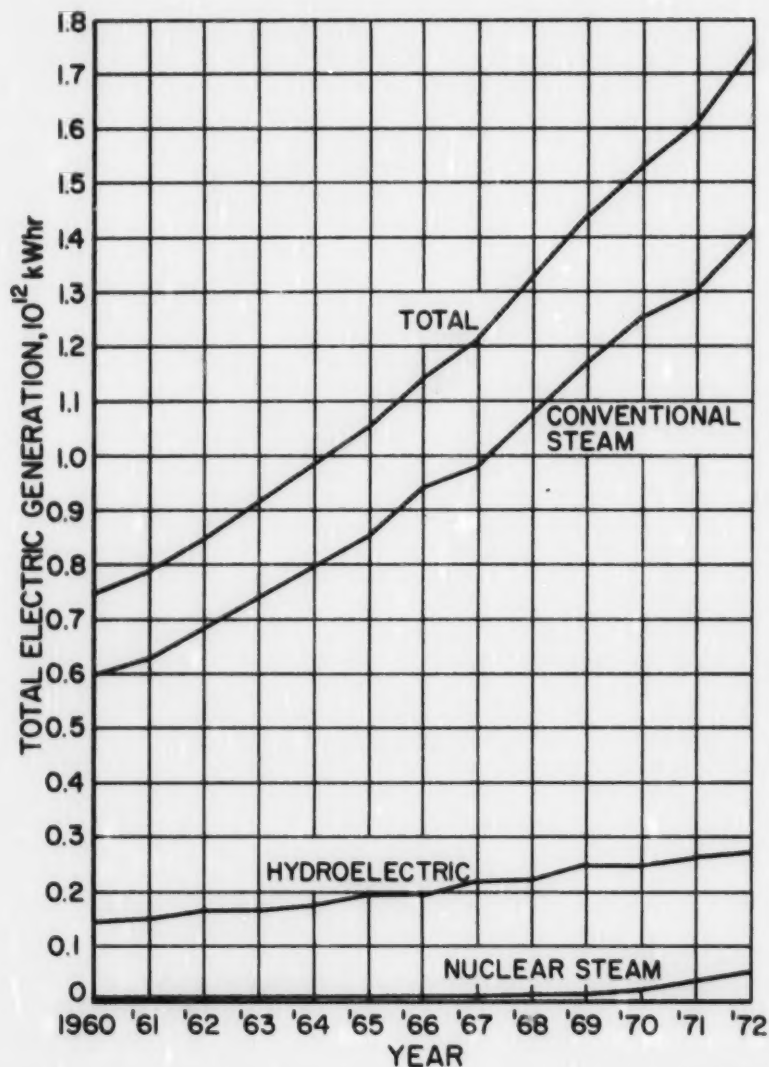
Compared to particulates, NO_x, and SO_x, the emission rates of carbon monoxide and hydrocarbons from industrial boilers are low. In general, these emissions are controllable by maintaining proper combustion. This includes careful monitoring of the air/fuel ratio to ensure the presence of enough combustion air to completely burn the fuel. Proper mixing of the air and fuel in the combustion chamber also is important for maintaining these emissions at a minimum. In some instances, it may be necessary to purchase control equipment to achieve this end, but in general, continuous observation and maintenance are all that are required.

Electricity Generation

In 1971, nearly 1800 trillion Btu of electrical energy was consumed by industry, about 13% of the total energy consumed.⁷ This is based on a conversion rate of 1 kWhr = 3413 Btu. However, this conversion rate does not consider the average efficiency of electricity generation, which is about 33%. At this generation efficiency, the conversion rate becomes 1 kWhr = 10,400 Btu. That is, 10,400 Btu of fossil fuel, or its equivalent, is required to generate 1 kWhr of electricity, which when consumed will only do the work equivalent to 3413 Btu.

There are four sources of energy for the generation of electricity. By far, the largest percentage of electricity is generated by the combustion of fossil fuel in boilers to drive steam engines and turbines. Hydroelectric power is second, with nuclear power a distant third. (See Figure 2.) A fourth source, not shown in Figure 2, is generation by internal combustion engines, but this source is so small by comparison (0.4% of the total) that it is not considered important. Unfortunately, the electric energy consumed by industry cannot be broken down by its source; thus the full impact of increases in electric energy consumption by industry on fuel consumption and on air pollutant emissions is difficult to assess. The one exception is the aluminum industry, where nearly one-half of the electricity consumed is generated hydroelectrically.⁶ Because of the relatively low cost of this electricity, aluminum plants tend to be close to hydroelectric plants. Because of the relative importance of conventional steam generation of electricity, this discussion considers only this source.

Historically, electric utilities have relied on coal as a source of energy, but in recent years, the use of natural gas and fuel oil has increased significantly. (See Figure 3.) Fuel oil consumption alone increased threefold between 1968 and 1972. This increase in the amount of electricity generated by using oil represents 10-18% of the total amount of electricity generated by fossil fuels. This switch, in large part, is a result of the restrictions on the quality of effluents from the generating station. Similarly, this also is the reason for the increase in natural gas consumption. However, whereas the data indicate a continued increase in fuel oil consumption, natural gas consumption is declining. This

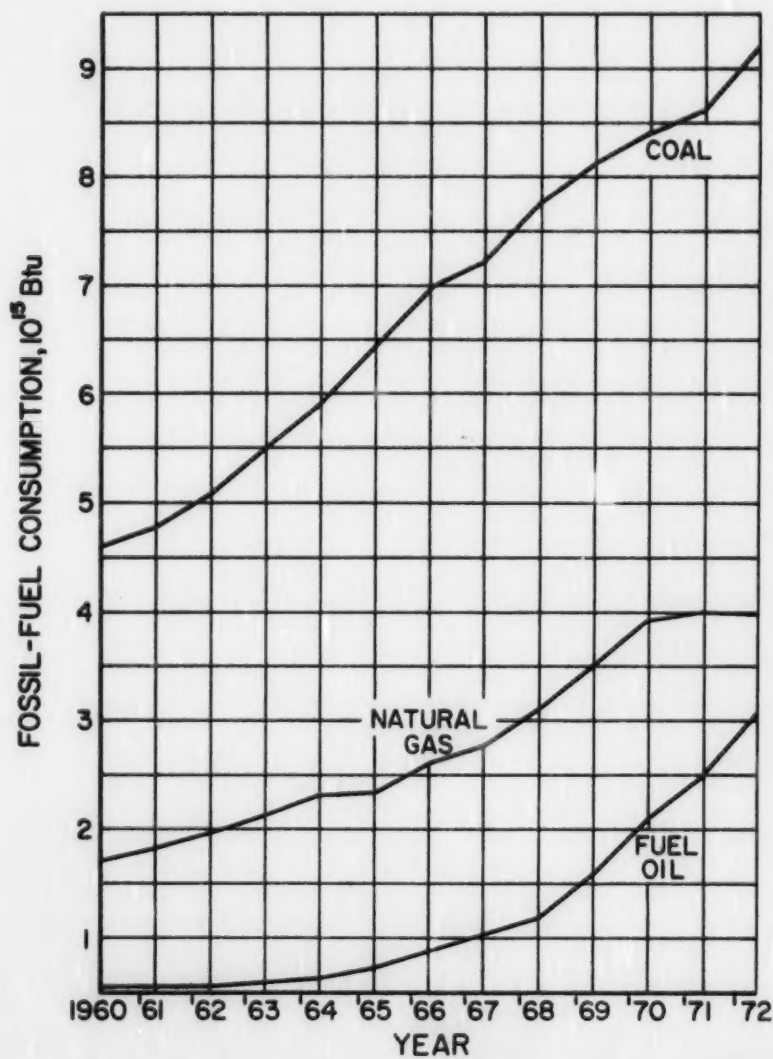


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Figure 2. TOTAL ELECTRICITY GENERATION BY TYPE OF PRIME MOVER DRIVING GENERATOR¹

decline is a result of the extreme shortage of this fuel, a shortage that is likely to continue for some time. As a result, its use for electricity generation is likely to continue to decline.

As previously stated, the average efficiency of electricity generation is about 33%. The efficiency could possibly be increased, but not without great expense and probably not more than 40%. The matter of efficiency is very important in considering alternative processes in industry. What appears to be a reduction in energy consumption by using an electric process may in fact result in a net increase in total energy consumption.



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Figure 3. FOSSIL FUELS CONSUMED
FOR ELECTRICITY GENERATION

A case in point is the use of electric melting in the glass industry, which reportedly consumes about 2.9 million Btu of electrical energy per ton of glass melted. However, when the energy consumed for electric generation is included, the total energy consumption for melting increases to more than 8.7 million Btu/ton of glass melted. Compared to a fossil-fuel-fired unit that can melt the same type of glass at a fuel consumption rate of 6.0 million Btu/ton of glass, the net result of switching to electric melting is an increase in energy consumption. And where a glass plant might switch to electric melting to reduce air pollutant emissions, the net result might be an increase in emissions due to the increase in combustion of fossil fuels for electricity generation. Thus, trends by industry toward the use of electric processes, as opposed to direct-fired processes, apparently will result in increases in fossil-fuel consumption and, in fact, may result in increased air pollutant emissions.

Air Pollutant Emissions From Electricity Generation

The electric utilities industry comprises about 675 fossil-fuel plants, which together produce more than 80% of all U.S. electric power; these plants also are one of the nation's worst sources of air pollution.⁵ In 1968, the most recent year for which data are available, these plants emitted 5.6 million tons of particulate matter, 16.8 million tons of sulfur dioxide, and 4.0 million tons of NO_x ,³ or 20%, 50%, and 20%, respectively, of these pollutants produced by all U.S. sources.⁵ The amount of emissions from any plant is determined by the type of fuel burned and the degree of control practiced. Table 3 shows the emissions from power-plant boilers according to the type of fuel being burned. This table also shows that the type of combustion system employed can affect emissions. As shown by the data, tangentially fired units produce lower NO_x emissions than horizontally fired units.

Particulates

Coal is by far the largest source of particulate matter, producing 100 times as much as oil and 500 times as much as natural gas when burned without the use of pollution control equipment. Included in the particulate matter resulting from the combustion of coal and, to a much lesser extent, fuel oil, are fly ash and carbon particles resulting from the incomplete combustion of the fuel.

Table 3. EMISSION FACTORS FROM
POWER UTILITY BOILERS⁸

Pollutant	Fuel		
	Coal, lb/10 ⁶ Btu coal burned	Fuel Oil, lb/10 ⁶ Btu	Natural Gas, lb/10 ⁶ Btu
Particulates	0.62A*	0.05	0.015
SO _x	14.8S*	1.06S*	0.0006
Carbon Monoxide	0.04	0.02	0.017
Hydrocarbons	0.01	0.01	0.001
NO _x	0.69	0.70 [†]	0.600 [‡]
Aldehydes	0.0002	0.007	--

* A and S are the weight percent of ash and sulfur, respectively, in the fuel being burned and are to be multiplied by the numbers shown to obtain corrected values.

† Use 50 for tangentially fired units.

‡ Use 300 for tangentially fired units.

The technology for particulate control for coal combustion is well developed. Electrostatic precipitators, baghouses, and wet scrubbers that are available prevent the emission of 99.5% or more of all soot and ash produced in the combustion of this fuel.⁵ The efficiencies of these controls are reduced considerably when applied to oil-fired units. Still, all these controls can remove at least 90% of the particulate emissions from oil-fired utility boilers when properly adapted.

SO_x

The air pollutant of greatest concern in the SO_x group is sulfur dioxide. The amount of sulfur in the fuel is the determining factor in the sulfur dioxide emission rate. Of the fossil fuels, coal's sulfur content is the highest, ranging from 0.5 to 5%, whereas that of oil varies from only 0.1 to 3%. Natural gas contains virtually no sulfur.

The state-of-the-art for controlling sulfur dioxide emissions from power plants is in a transitional period. The two alternatives for control are 1) to burn low-sulfur fuels or 2) to remove the sulfur dioxide from the flue gases before they escape into the atmosphere. The use of low-

sulfur fuels is a costly and temporary solution because their availability is limited. In addition, mining, refining, and transportation facilities do not exist in sufficient capacity to permit immediate industry-wide changeover. Similarly, several systems have been proposed and developed to remove sulfur dioxide from the flue gases, but information on their costs, efficiencies, and technical problems is sketchy. These uncertainties have caused delays both in the perfection of available techniques and in the commitment by utilities to implement currently available controls. However, changes are beginning to occur. Utilities are switching to low-sulfur fuels, resulting in a reduction of sulfur dioxide emissions of 50-85% below previous levels. In addition, control techniques are beginning to be implemented, generally aiming for reductions up to 90% by 1980.⁵ The most promising methods are limestone scrubbing, magnesia scrubbing, and catalytic oxidation. All these methods are expensive and control efficiencies conservatively range from 70 to 80%, although higher efficiencies have been reported with some experimental systems.⁵

NO_x

These pollutants are produced in the combustion of fossil fuels at high temperatures. Unlike SO_x and particulates, which result from impurities in the fuel, NO_x are formed by the reaction of nitrogen and oxygen present in the combustion air, as well as by the oxidation of nitrogen in the fuel. The rate of formation depends on a number of combustion characteristics, many of which are not completely understood. As a result, NO_x formation varies among different boilers as well as different fuels.

Much research is currently being conducted to develop methods for controlling NO_x emissions. The three most successful methods involve modification of combustion methods and tend to apply only to natural gas and oil combustion:

1. Reducing the amount of excess air to the lowest level without causing incomplete combustion
2. The use of two-stage combustion, in which combustion air insufficient for complete combustion is fed directly into the burner and the remainder is fed in at a point downstream of the burner to burn the remaining fuel
3. Recirculating some of the flue gases back into the boiler, reducing flame temperature and oxygen concentrations.

None of these methods appears to work well with coal-fired systems. Implementation of these control methods by power plants is occurring only at low rates, except in southern California, where implementation in some plants has resulted in a 70% reduction in emissions from oil- and gas-fired units.

Much can be done to reduce power-plant emissions in the future. Meanwhile, industry is converting many processes to electrical energy. In many cases, the processes themselves consume less energy and are cleaner than the processes that they replace. But if the energy requirements and emission rates of the power plant also are considered, some of these processes, from a national point of view, will become unattractive. However, evaluations of these processes cannot be presented here; rather, they should be made on an individual basis with particular attention to the source of the electricity being consumed.

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